A geophysical study of the continental margin west of Norway

Robinson, J.

A GEOPHYSICAL STUDY OF THE CONTINENTAL MARGIN WEST OF NORWAY

J. ROBINSON

A thesis submitted for the degree of Doctor of Philosophy in the University of Durham.

London March 1980

Contents

List of Figures

Acknowledgements

I wish to thank Professor M.H.P. Bott for supervising this work and for all of his splendid help and advice. I am deeply indebted to the Natural Environment Research Council for financing the work and for providing a research studentship, and my thanks are also extended to the University of Durham, and the Department of Geological Sciences therein, for providing the opportunity and facilities for me to undertake this study. Mr. J. H. Peacock provided invaluable technical assistance throughout the project, together with many useful and thought-provoking ideas regarding the area of study.

This work would not have been possible without the assistance and technical expertise of the scientists and technicians of the Shipboard Computer Unit of the Institute of Oceanographic Sciences at Barry, South Wales, and I wish to express my warmest thanks to them for their efforts. Equally important in the accomplishment of this project has been the unstinting work of Mr. G. Ruth, Mr. D. Asbery and the other technicians at the Department of Geological Sciences in Durham, who succeeded in repairing machinery almost as quickly as I could wreck it.

I should like to thank all of the staff, and my fellow research students, at the Department of Geological Sciences, Durham for all of their assistance, encouragement and ideas during my time in the department. Finally I wish to thank my many friends in and around Durham for making my three years there so enjoyable.

Abstract

A geophysical investigation of the continental margin between Norway and the Faeroe Islands has been carried out, utilizing gravity, magnetic, bathymetric, seismic refraction and seismic reflection data. Detailed analysis of this data has shown that the boundary between the oceanic-type crust beneath the Norwegian Basin and the continental-type crust of North West Europe does not lie along the Faeroe-Shetland Escarpment as suggested by Talwani and co-authors. The line of splitting between the Møre region and Greenland has been identified as lying just to the south-east of magnetic anomaly 24 within the eastern Norwegian Basin. This is supported by seismic reflection and gravity evidence.

Gravity data over the margin has been interpreted as revealing a zone of anomalously thin crust which may mark a north-eastern extension of the Faeroe-Shetland Channel. It is separated from the Norwegian Basin by a zone of rather thick crust forming a spur from the Faeroes Block. It is proposed that the zone of anomalously thin crust be known as the East Faeroes Trough.

Within the Norwegian Basin the magnetic data confirms that the sea-floor spreading anomalies form a fan-shaped pattern narrower in the south than in the north. Seismic reflection data within the central portion of the basin shows rough and undulating basement topography, with many basement peaks, some of which form the seamounts detected on earlier bathymetric surveys. It has been tentatively suggested that the basement peaks and lack of correlatable magnetic anomalies in the centre of the basin are due to the continual westward migration of the spreading axis.

Chapter 1

Introduction

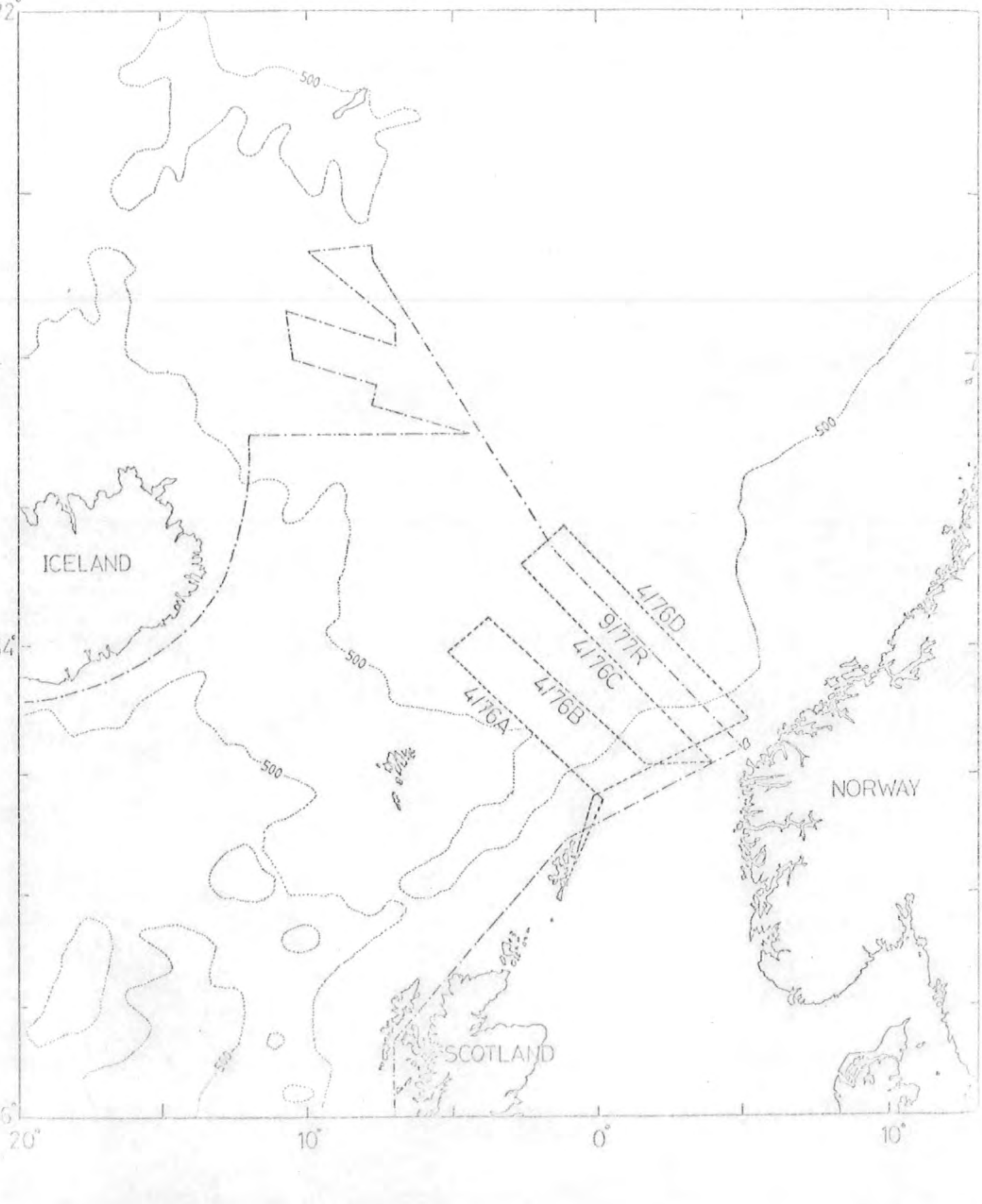
1.1 Introduction.

This thesis describes the collection, reduction and interpretation of data gathered by the Department of Geological Sciences during two cruises over the continental margin between the Faeroe Islands and Norway during September 1976 and August 1977. Gravity, magnetic, bathymetric and seismic reflection observations were carried out continuously along a number of northwest-southeast traverses across the margin. A small number of short range seismic refraction experiments were also undertaken. The area investigated is bounded by latitudes 61°N, and 69°N, longitude 6°W and the Norwegian coast on the east. The ship's track on both cruises is shown in figure 1.1. This survey continues the investigation of the continental shelf off N.W. Europe undertaken by Durham University during the past decade. Throughout this work the timescale of Heirtzler et. al. (1968) has been used, although it is noted that recent work, eg Soper et. al. (1976), La Brecque et. al. (1977), indicates that this timescale may be in error by up to 6 million years in the early Tertiary.

1.2 The structure of the northern North Atlantic Ocean and adjacent regions.

The physiography of the northern North Atlantic Ocean and its surrounding areas is shown in figure 1.2. North of Iceland, only one portion of the region is morphologically typical of the north Atlantic, that area with the Greenland and Lofoten Basins flanking a centrally situated mid-ocean ridge known as the Mohns Ridge. Elsewhere the present spreading axis is not centrally located between two ocean

Figure 1.1 Ship's track during cruise 4/76 and cruise 9/77.


72°
64°
56°
20°
10°
0°
10°
500
ICELAND
NORWAY
SCOTLAND
4/76D
9/77R
4/76C
4/76B
4/76A

basins but is near to the west side. There appear to be fragments of continental crust within the region together with anomalous areas of oceanic crust, one of which, the Greenland-Iceland-Faeroes aseismic ridge, separates the Norwegian-Greenland Sea from the North Atlantic Ocean further to the south. Until quite recently, little was known of the area to the north of Iceland. The first systematic echo-sounder profiles of the region were presented by Boyd (1948) and the first detailed bathymetric chart of the Norwegian-Greenland Sea was produced by Litvin in 1964. The development of the theory of plate tectonics has led to a much greater interest in the region and consequently to much more exploration.

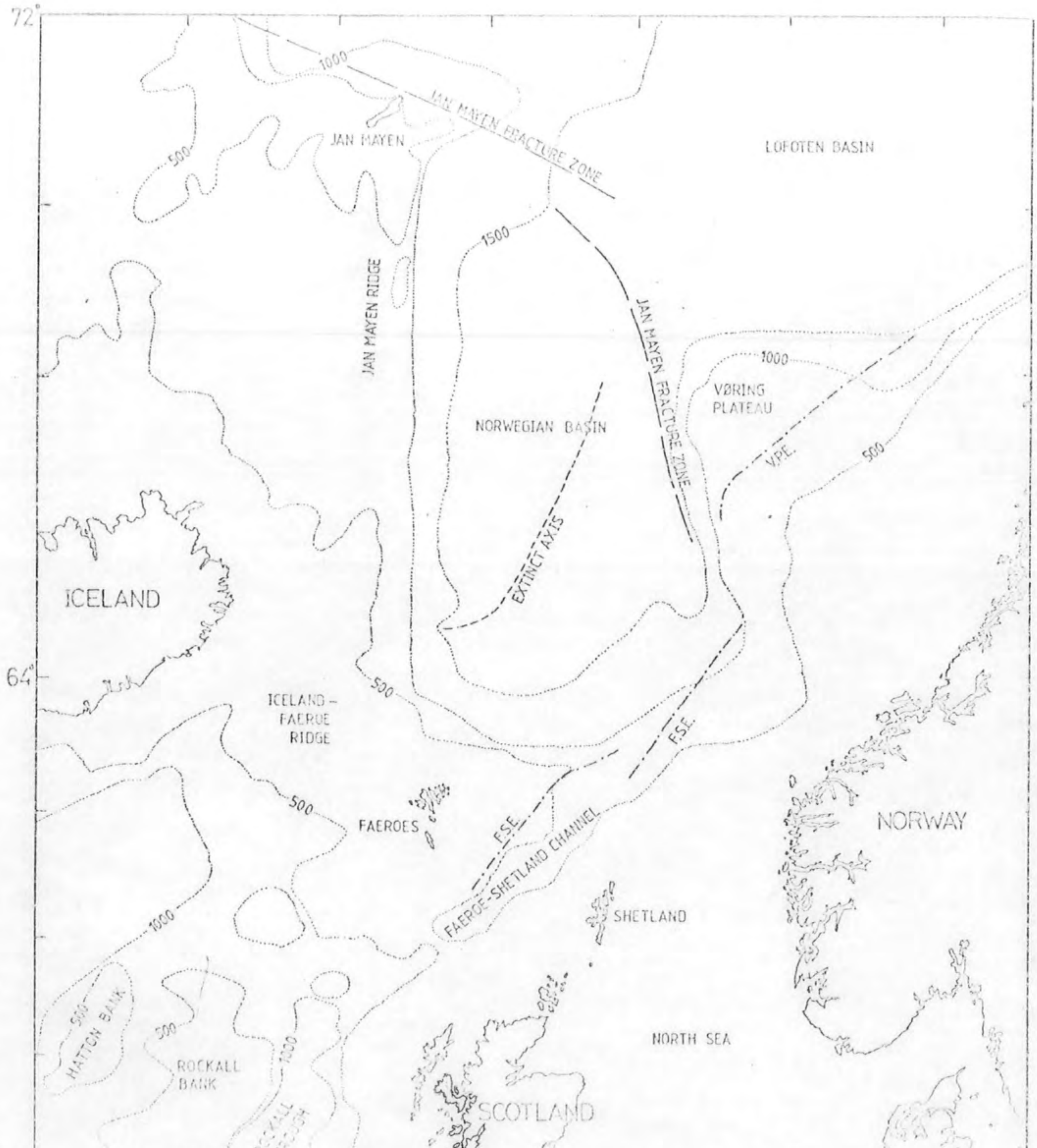
The Iceland-Faeroe Ridge is a broad aseismic submarine ridge of northwesterly trend which links Iceland and the Faeroes Block. It has a smooth sea-bed and a depth to the crest along the ridge of about 400 metres (Fleischer, 1971; Fleischer et. al., 1974). The sediment cover over the crest is thin, typically less than 200 m (Talwani and Udintsev, 1976), although much thicker sediment accumulations occur down either flank. A particularly thick sequence is seen along the southeastern end of the Norwegian Sea flank, terminating against the Faeroes Block (Eldholm and Windisch, 1974). Seismic reflection studies (Fleischer et. al., 1974) indicate the presence of a sediment filled basement depression 40 km wide and at least 500 m deep along the crest of the ridge.

High amplitude, high frequency magnetic anomalies are known to exist over the ridge but without any extensive linear pattern (Fleischer et. al., 1974). The magnetic highs over the ridge are related to gravity lows (and vice versa) indicating that the basaltic material is reversely magnetized (Fleischer, 1971). This is in agreement with the

Figure 1.2 The physiography of the North East Atlantic Ocean and surrounding areas.

F.S.E. = Faeroe Shetland Escarpment

V.P.E. = Vøring Plateau Escarpment


72°
64°
56°
20°
10°
0°
10°
1000
JAN MAYEN FRACTURE ZONE
JAN MAYEN
LOFOTEN BASIN
500
1500
JAN MAYEN RIDGE
JAN MAYEN FRACTURE ZONE
1000
VØRING PLATEAU
NORWEGIAN BASIN
V.P.E.
500
EXTINCT AXIS
ICELAND
500
ICELAND – FAEROE RIDGE
F.S.E.
500
FAEROES
F.S.E.
FAEROE-SHETLAND CHANNEL
NORWAY
SHETLAND
1000
500
HATTON BANK
500
ROCKALL BANK
1000
ROCKALL TROUGH
NORTH SEA
SCOTLAND

results of Tarling and Gale (1968) who pointed out that the basaltic plateau lavas of the Faeroe Islands are characteristically reversely magnetized. Gravity data shows that the ridge is in approximate isostatic equilibrium, and that the steep gravity gradient between the ridge and the Norwegian Basin must be caused by a thickened crust underlying the ridge rather than by an anomalously low density mantle (Bott et. al., 1971). This has been confirmed by the seismic refraction data gathered during the multi-national N.A.S.P. experiment which indicated a crustal thickness of 27 km or more beneath the ridge (Bott et. al., 1976).

Two holes were drilled into the ridge during Leg 38 of the Deep Sea Drilling Project, one on the northern flank and the other on the southern flank. Technical difficulties prevented a hole being sunk into the crestal region of the ridge (Talwani and Udintsev, 1976). These borings show the existence on the ridge of basalts of a similar nature to the basalts from mid-ocean ridges. A lower Tertiary lateritic palaeosol was found in the core recovered from the northern flank (Nilsen and Kerr, 1978) which, with other evidence (Talwani and Udintsev, 1976), suggests that the basalts were extruded in a sub-aerial environment. This implies that the ridge has subsided by at least 900 m since the basalts were formed, probably because of the cooling of the oceanic lithosphere with age (Vogt, 1972).

The ridge is believed to have formed by the sea-floor spreading process, but instead of being formed below sea-level the lavas were extruded sub-aerially and therefore did not produce the linear magnetic anomalies characteristic of oceanic basins. The cause of the unusual crustal thickness is unknown, although it has been postulated that a mantle plume was active below the region during the time of formation of the ridge (Morgan, 1971). It is also possible that the thickness is the result of a convective overturn within the upper mantle (Bott, 1973). Both of these explanations can account for the unusually high rate of upper mantle differentiation needed to generate the quantities of basalt observed within the region (Bott, 1973). This prolific differentiation is likely to be the cause of the massive lava flows of the Brito-Arctic province. Formation of the ridge is believed to have taken place between 60 and 45 M.y. ago (Bott, 1974).

South of the Greenland-Iceland-Faeroe Ridge, the northern North Atlantic has developed without any significant interruption since the splitting between Rockall and Greenland in the early Tertiary. The present spreading axis, the Reykjanes Ridge, is centrally situated between two deep oceanic basins (Heirtzler et. al., 1966) and apparently has had a central location since anomaly 22 time when a straightening of the spreading axis took place (Featherstone et. al., 1977). The oldest magnetic anomaly that has been identified between Rockall and Greenland is anomaly 24 (Vogt and Avery, 1974), indicating that the final rifting between Greenland and Rockall took place about 60 M.y. ago.

The Atlantic here is bounded to the east by the Rockall-Faeroe rise, an extensive shoal area stretching several hundred kilometres northeastwards from the Hatton and Rockall Banks to the Faeroes Block. In the south, the Rockall and Hatton Banks are separated by a northeast trending sedimentary basin (Roberts et. al., 1970) known to contain sediments at least as old as Palaeocene (D.S.D.P. Scientific Staff, 1970). The only sub-aerial expression of the region is Rockall Islet at the northeastern end of the Rockall Bank. This is composed of lower Eocene aegirine granite (Miller and Mohr, 1965) and is probably part of a Tertiary igneous centre similar to those found on the Scottish mainland (Roberts, 1969). Further north, George Bligh Bank and Lousy Bank rise to a depth of around 500 m but little is known of their structure. To the northwest, basalt fragments have been dredged from Bill Baileys Bank (Dangeard, 1928). In the north, the Faeroe Bank is probably covered by basic igneous rocks extruded from NNW trending fissures (Dobinson, 1970).

This shoal area is now accepted as being of continental origin. Bullard et. al. (1965) found a gap in their computer fit of the continents bordering the North Atlantic, into which Rockall Bank, Hatton Bank and George Bligh Bank could be fitted. A later reconstruction by Bott and Watts (1971) included the whole of the Rockall-Faeroe Rise as a continental block. Seismic refraction data (Scrutton and Roberts, 1971) indicates that the depth to the Mohorovicic discontinuity beneath the Rockall Bank is about 31 km, which agrees with the results of gravity ovservations over the region (Scrutton, 1972). Isotope work on samples from Rockall Islet (Sabine, 1965; Moorbath and Welke, 1969) also indicated that the region was continental. Proof that these indications were correct was presented by Roberts et. al. (1973) and by Miller et. al. (1973) who reported the presence of rocks of Grenville age in cores taken from a drill-hole on Rockall Bank. A detailed description of the microcontinent was published by Roberts (1975).

The Faeroes Block lies at the junction of the oceanic Iceland-Faeroe Ridge and the continental Rockall-Faeroe Rise. It is separated from the main body of the Rockall microcontinent by the Faeroe Bank Channel, while a small steep bathymetric escarpment marks the junction of the block and Iceland-Faeroe Ridge (Bott et. al., 1974; Fleischer et. al., 1974). Thus it is not immediately clear whether the Faeroes Block is of oceanic or continental origin.

Water depths over the Faeroes Block rarely exceed 200 m. The emergent parts of the block form the Faeroe Islands, which exhibit the same northwest-southeast trend as the Iceland-Faeroe Ridge. The islands are almost entirely composed of flat-lying basaltic plateau lavas (Rasmussen and Noe-Nygaard, 1970) which have been dated as being between 50 and 60 M.y. old (Tarling and Gale, 1968). The lavas can be sub-divided into three series known as the Lower, Middle and Upper Series (Rasmussen and Noe-Nygaard, 1970). The Lower Series is about 900 m thick and was formed by intermittent fissure eruptions of lava. This was followed after a long quiescent period by the generation of the Middle Series of lavas, up to 1350 m thick from northwest-southeast vents. The succeeding Upper Series was created in a similar fashion to the Lower Series and reaches a maximum thickness of 650 m.

The base of the lava pile is not visible on the Faeroe Islands and so the total thickness of the lavas is not known. Seismic refraction experiments (Palmason, 1965) showed the lava pile to be between 2.5 and 4.5 km thick, with a velocity of about 4.9 km/s. Beneath the lavas was seen a layer with a seismic velocity of 6.4 km/s that was interpreted as basement, suggesting an upper crustal structure similar to that known to exist beneath Iceland (Bath, 1960; Palmason, 1967). This suggestion is incompatible with the continental reconstruction of Bott and Watts (1971) which implies that the Faeroes Block is continental in nature. The gravity anomalies observed between the Faeroes Block and the Iceland-Faeroe Ridge (Bott et. al., 1971) also suggest a continental origin for the block. Casten (1973) interpreted a single unreversed seismic refraction line on the Faeroe Islands in terms of a basement velocity of 5.9 km/s, more in accord with a continental, rather than an oceanic, origin. Bott et. al. (1974) presented the results of the multi-national N.A.S.P. seismic refraction project which indicated that the crust beneath the Faeroe Islands is between 30 km and 40 km thick, that the basement exhibits a seismic velocity of between 6.0 and 6.2 km/s, and that there is an absence of a 6.4 - 6.7 km/s layer giving first arrivals. The same authors also reinterpreted the data provided by Palmason (1965) and they showed that if the first arrivals only are considered, then the velocity of the basement beneath the reversed line is of the order of 5.9 km/s. Gravity surveys (Bott et. al., 1971; Fleischer et. al., 1974) show a steep gravity gradient between the Faeroes Block and the Iceland-Faeroe Ridge coincident with the bathymetric scarp between the two features. Converted P-waves generated at the junction of the Ridge and the Block have been reported from the N.A.S.P. project (Bott et. al., 1976), supporting the view that the junction between the continental and oceanic crusts occurs at the bathymetric scarp between the two features. An alternative view was proposed by Talwani and Eldholm (1977), who used the same data as Bott et. al. (1974) and Fleischer et. al. (1974) to suggest that the Faeroes Block is oceanic in origin. A continental reconstruction without the Faeroes Block was used by these authors to support their ideas. Furthermore, they suggested that the ocean-continent boundary lies to the southeast of the Faeroe Islands, either in the region where Bott et. al. (1974) found an eastward change to a basement velocity of 5.3 - 5.5 km/s, or along the southern section of the Faeroe-Shetland Escarpment as denoted by Talwani and Eldholm (1977).

The Faeroe-Shetland Channel, separating the Faeroes Block from the Hebridean-Shetland continental Shelf, is another controversial region.

It is a northeast-southwest area of deep water with a smooth sea bed topography which is at its widest and deepest at the northeastern end where it meets the Norwegian Basin (Bott and Watts, 1971). The channel appears to be a northward continuation of the Rockall Trough, but separated from it by the Wyville-Thomson Ridge, a northwest-southeast bathymetric rise joining the Faeroe Bank to the United Kingdom continental shelf. The Wyville-Thomson Ridge consists of two parallel basement ridges (Ellett and Roberts, 1973) of possible pre-Tertiary age, which are covered by a fairly thin veneer of sediments. To the south the Rockall Trough widens and deepens, reaching a depth of 2800 m west of Northern Ireland.

The origin of the Faeroe-Shetland Channel is unclear as it is neither typically oceanic nor typically continental. Bott and Watts (1971) suggested that there is a thinning of the crust of about 8 km between the Orkneys and the channel, giving a depth to the Moho beneath the channel of 19 - 20 km. The crustal thinning would explain the high Bouguer anomaly observed over the channel. Talwani and Eldholm (1972) disagreed with this suggestion, claiming that the entire Bouguer anomaly could be caused by an intrabasement density contrast and that no crustal thinning is needed to explain the observed anomaly. They also proposed that the western boundary of the channel marks the edge of the Tertiary opening of the North Atlantic. The bathymetric contours of the Rockall Trough and the Faeroe-Shetland Channel are such that it seems likely that the two features were formed at the same time and by the same process. The two possible origins are that they consist of stretched and subsided continental material, or that they are oceanic in nature. None of the linear magnetic anomalies characteristic of sea-floor spreading have been identified within either the Rockall Trough or the Faeroe-Shetland Channel, so that if they were formed by this process then it must have been during a period when no geomagnetic polarity reversals occurred. Anomaly 32 is seen to cross the southern mouth of the Trough (Laughton, 1972) so the Trough must have been in existence by this time. This anomaly has since been re-identified by Kristoffersen (1977) as anomaly 34. Seismic refraction and reflection data indicates that the Trough has a depositional history extending back into the Mesozoic (Scrutton and Roberts, 1971) and it appears that the Trough formed by sea-floor spreading in the Mesozoic during the first abortive split between Greenland and Eurasia. This view is supported by various authors, eg Hallam, 1971; Bott, 1975b; who suggest that the opening took place during the well-documented magnetic quiet period in the Lower-Middle Cretaceous. Russell (1976) however proposed that the Trough opened in the early Permian. Talwani and Eldholm (1977) imply that they believe the Faeroe-Shetland Channel is continental in origin and that the Channel can be treated independently from the Rockall Trough.

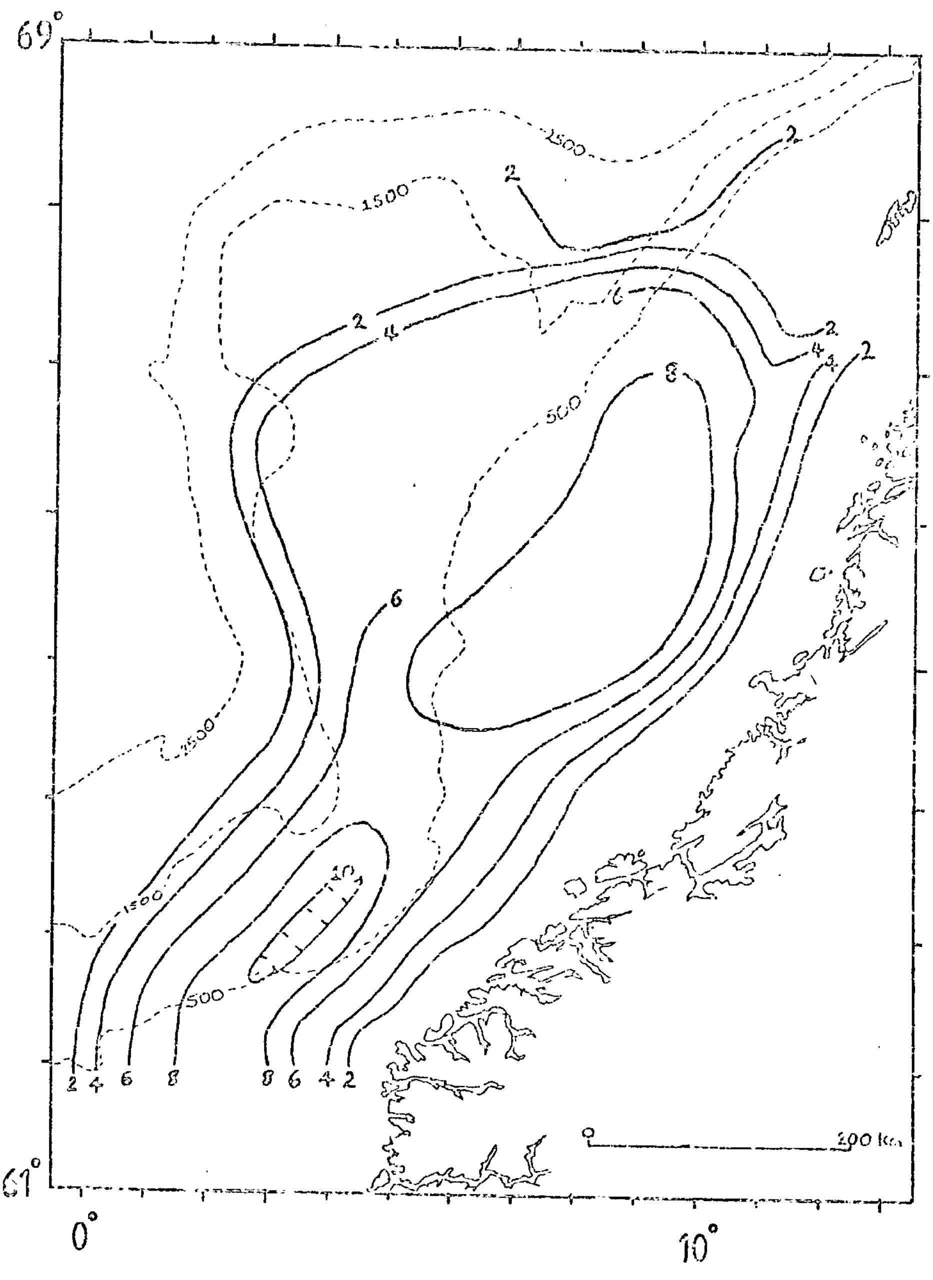
Southeast of the Faeroe-Shetland Channel is the Hebridean-Shetland continental shelf, a broad shallow area bordering northwest Scotland with water depths generally less than 200 m. To the southwest Precambrian rocks outcrop in the Outer Hebrides (Jehu and Craig, 1923), on North Rona (Nisbet, 1961) and on the skerries (Geological Survey, 1957), while in the east, Devonian granitic intrusions are found in Sutherland, Caithness and the Shetland Isles, together with Devonian lavas in the Orkneys (Wilson et. al., 1935) and in the Shetlands (Flinn et. al., 1968). Tertiary igneous activity within the Brito-Arctic province created dyke swarms and centres in northwest Scotland (Stewart, 1965). The entire region was extensively glaciated during the Pleistocene. Throughout northern Scotland the dominant trend directions of the major faults are NNE - SSW and northeast-southwest (Pitcher, 1969). The Great Glen Fault has been interpreted as a sinistral transcurrent fault (Kennedy, 1946) while Flinn (1969, 1970) has suggested that the sinistral component extends out beyond the Moray Firth to be seen in the Shetland isles as the north-south trending Walls Boundary Fault.

A much greater knowledge of the deep structure of the region has been gained from recent geophysical investigations of the shelf eg. Watts, 1971; Himsworth, 1973. The Caledonian front crosses the north Scottish coast onto the shelf. On land it separates the Lewisian and Torridonian basement rocks to the west from the Moinian and Dalradian rocks of the Caledonian belt to the east, and this subdivision is believed to apply to the basement rocks beneath the shelf (Bott, 1975a). Seismic refraction data (Smith and Bott, 1975) shows that the crust is about 26 km thick beneath the shelf. There is a conspicuous north-north-east trending gravity high west of the Shetland Isles that is continuous for 250 km (Watts, 1971). Immediately to the west of the high is a pronounced gravity low, with a steep gravity gradient observed between the two features. Seismic reflection profiling indicates that basement rocks outcrop beneath at least 110 km of the length of the gravity high. The high is thus attributed to the shallow occurrence of high density metamorphic rocks, possibly Lewisian granulites of Scourian type (Bott and Watts, 1971). Several gravity lows have been found on the shelf and have been interpreted as partially fault-bounded sedimentary basins filled with Mesozoic sediments (Bott and Watts, 1970). Recent drilling by the oil industry would seem to confirm this suggestion. Seismic reflection profiling (Watts, 1971) has shown the existence of an extensive unconformity close to the sea-bed throughout the region, with seaward dipping, probably Quaternary sediments above the unconformity and southeast-dipping pre-Quaternary and possibly pre-Tertiary sediments below.

To the east lies the northward continuation of the North Sea, an area of subsidence and sedimentation since the early Mesozoic or late Palaeozoic, which is now the subject of intense economic activity as a result of the discovery of large quantities of hydrocarbons. The North Sea is shallow, with a depth of less than 200 m, although it deepens northwards towards the shelf edge and in the east where the deep Norwegian Channel runs NNW - SSE across the shelf near the west coast of Norway. The continental shelf off Norway narrows dramatically northwards to a width of less than 60 km west of Stad and then it widens again to the north. The Vøring Plateau, a wide area with water depths of between 1200 and 1700 m occurs on the continental slope between 66°N and 68°N.

Seismic reflection and refraction surveys have shown there to be a basement rise beneath the Norwegian continental slope (Talwani and Eldholm, 1972; Sellevoll, 1975) terminating in an east-facing escarpment, to the east of which is seen a thick sedimentary sequence. Aeromagnetic data (Am, 1970) also indicates that the basement rocks dip steeply eastwards below the shelf to form the Møre (or Stadt) Basin (figure 1.3). A similar situation exists further north on the Vøring Plateau, which is divided into two by an east-facing escarpment running parallel to the coast. High velocity rocks are seen west of the escarpments (Talwani and Eldholm, 1972; Gronlie and Talwani, 1978) while east of the escarpments the seismic and magnetic data shows that the low velocity sediments are of great thickness. The two escarpments

Figure 1.3 Depth to magnetic basement west of Norway.
Redrawn from Am (1970).
Contours in kilometres.


69°
61°
0°
10°
0
200 km
1500
500
2
4
6
8
10

are known as the Faeroe-Shetland Escarpment and the Vøring Plateau Escarpment and are shown in figure 1.2. The total thickness of sediments in the Møre and Inner Vøring Plateau Basins is not known as none of the seismic experiments have been able to detect the basement below the sediments, although a refraction line across the Vøring Plateau was interpreted by Hinz (1972) as showing the presence of high velocity material at a depth of 10 km beneath the Inner Vøring Plateau. Estimates based on aeromagnetic data (Am, 1970) put the basement at approximately 9 - 10 km below sea-level in the deepest part of the basin, which agrees with the seismic refraction data (Sellevoll, 1975). The escarpments forming the western boundaries of the basins have been interpreted as marking the site of the initial Tertiary rift in the Norwegian-Greenland Sea (Talwani and Eldholm, 1972, 1977; Sellevoll, 1975; Talwani and Udintsev, 1976) with continental crust underlying the sedimentary basins to the east and oceanic crust forming the basement rise to the west. This conclusion is based on the change in character of the magnetic field across the escarpments, the quiet zone seen to the east contrasting with the high amplitude, high frequency anomalies in the west. It is also possible to see on the seismic profiler records a basement reflector continuing onto the basement rise from the obviously oceanic Norwegian Basin. This belief was questioned by Hinz (1972) in connection with the Vøring Plateau, but his data is in no way conclusive. The Deep Sea Drilling Project drilled several holes within the region but failed to produce any conclusive evidence concerning the initial rifting of the area. Basalts, dated as approximately 45 M.y. old were penetrated on the Outer Vøring Plateau, which it is argued (Talwani and Udintsev, 1976) supports the view that this section of the Vøring Plateau is oceanic and not continental in nature.

It is likely that the Central and Viking Grabens of the North Sea may well continue northwards (Whiteman et. al., 1975), and that the thick sediment deposits east of the escarpments are a continuation of the deposits of the North Sea rift (Rønnevik et. al., 1975). It has also been suggested that at some point in time a proto-triple junction existed on the shelf northeast of the Shetland Isles (Whiteman et. al., 1975; Dingle, 1976) with the arms forming the present Viking Graben, the Faeroe-Shetland Channel and the Møre and Vøring Plateau Basins. The region is magnetically quiet, while the numerous belts of high gravity have been interpreted as reflecting intra-basement density contrasts. Analysis of the seismic refraction data (Talwani and Eldholm, 1972) showed that the sediments on the shelf have a similar velocity-age relationship to those of the North Sea, and if this is true then the deepest layers in the sedimentary pile are likely to be of Mesozoic age. The lowest refractor found by Eldholm (1970) had a velocity of 5.2 km/s and was interpreted as basement although this is rather a low velocity for continental basement.

The Norwegian land mass (figure 1.4) consists almost entirely of partly and wholly metamorphosed sediments of the Caledonian geosyncline together with numerous outcrops of Precambrian rocks. There are a few exceptions:- the very old metamorphic rocks in granulite facies that form the Lofoten Islands (Heier and Compston, 1969), the unmetamorphosed Devonian clastic sediments preserved in elongated grabens parallel to the coast near Trondheim, and the Jurassic-Cretaceous sequence seen on the Isle of Andøya (Holtedahl, 1960). Extensive glaciation has affected the entire area, producing the well-developed fiords. It is believed that there was an oblique uplift of the region during the Tertiary (Torske, 1972), and there

Figure 1.4 The geology of Norway.
Redrawn from Holtedahl (1960).


70°
60°
Cretaceous Jurassic
K
Shale, sandstone (Andoya)
Permian
Igneous rocks around Oslo
Devonian
Sandstone, shale etc.
Cambro-Silurian
Relatively unmetamorphosed rocks
Metamorphic rocks in the Caledonides
Basic rocks in the Caledonides
Acid gneissic rocks in the Caledonides
Basal granites and gneiss (Caledonian)
Eocambrian
Sedimentary rocks
Precambrian
" "
Lofoten eruptives
0
200 km
10°
20°

appears to be isostatic recovery taking place at present as a result of the removal of the last great ice-sheet about 10,000 years ago.

The eastern section of the Norwegian-Greenland Sea between the Jan Mayen Fracture Zone and the Iceland-Faeroe Ridge is known as the Norwegian Basin. This is a wide oceanic abyssal area with water depths exceeding 3000 m. A deep topographic depression runs northeast-southwest through the centre of the basin, flanked on either side by a range of seamounts. The water depths in the depression exceed 4000 m in places and there is a difference in elevation of up to 1500 m between the floor of the depression and the peaks of the seamounts (Eldholm and Windisch, 1974). This zone is believed to represent the remains of an extinct spreading axis about which the Norwegian Basin was formed (Johnson and Heezen, 1967: Vogt et. al., 1970b). A pronounced gravity low is present over the depression (Grønlie and Talwani, 1978) but elsewhere the gravity field is unremarkable. Linear magnetic anomalies are seen in the basin (Avery et. al., 1968) which appear to be symmetrical about the central valley (Vogt et. al., 1970b). The anomalies however are not parallel with the valley, but diverge towards the north forming a fan-shaped pattern (figure 3.7). The distance between matching anomalies on either side of the valley is up to 150 km greater in the north than in the south. Anomalies 20, 21 and 22 have been tentatively identified within the basin (Talwani and Eldholm, 1977) and it is possible that anomalies 23 and 24 also exist in this region. It is difficult to identify anomalies younger than anomaly 19 as the magnetic field in the centre of the fan is quiet, without distinct anomalies. Seismic refraction results (Ewing and Ewing, 1959; Hinz and Moe, 1971) show that the Moho is at 8-10 km below sea-level under the basin. The data presented by

Hinz and Moe included the results of a profile across the zone of seamounts, which were interpreted as showing high velocity blocks rising close to the sea-bed, a very different crustal structure to the typical oceanic structure found on the other profiles. The sea-floor spreading is thought to have commenced about 60 M.y. ago and to have died out before anomaly 7 time. There is little earthquake activity in the region today (Husebye et al., 1975).

The eastern extension of the Jan Mayen Fracture Zone forms the northern boundary of the Norwegian Basin, separating it from the Vøring Plateau and Lofoten Basin. It is characterized by a steep southwest-facing escarpment reflecting the difference in elevation of the two regions, the Vøring Plateau and Lofoten Basin being as much as 500 m higher than the Norwegian Basin (Eldholm and Windisch, 1974). In the southeast the fracture zone may consist of a series of blocks with steep escarpments at their edges rather than a single linear feature (Sellevoll, 1975). The fracture zone was originally discovered by Sykes (1965) who noted a lateral displacement in the epicentres of earthquakes associated with the mid-ocean ridge. The presence of these earthquakes indicates that the fracture zone is still active between the Mohns Ridge and the Iceland-Jan Mayen Ridge. The fracture zone has been interpreted as a transform fault and appears to have produced a compressional zone on the Norwegian continental shelf between the Møre and Vøring Basins (Ronnevik et al., 1975). It has recently become clear (Talwani and Eldholm, 1974) that the fracture zone is in two sections with different azimuths. It is believed that this is a result of the change in the direction of opening between Greenland and Norway that occurred when the Labrador Sea ceased to open and Greenland became part of the North American plate. A piston core recovered from the sea-bed immediately southwest of the fracture zone (Saito et. al., 1967) showed a thin layer of Pleistocene sediments unconformably overlying Palaeocene muds and clays, possibly indicative of the erosion suffered due to bottom-water currents.

The Jan Mayen Ridge forms the western boundary of the Norwegian Basin. It is a flat-topped bathymetric rise, which rises to a depth of 1000m and which runs due south from Jan Mayen Island to 69°N where it turns slightly westward and ends near 68.5°N. Seismic reflection studies (Johnson and Heezen, 1967) show basement rocks outcropping on the western side of the ridge, but the crest and eastern flank of the ridge are covered by a thin veneer of flat-lying sediments, the base of which forms a prominent reflector. Beneath the prominent reflector, lower horizons are visible dipping steeply eastwards, being truncated by the prominent flat-lying reflector. The ridge is magnetically quiet, which prompted Avery et. al. (1968) to suggest that it is purely a sediment ridge, in contrast to the interpretation of Johnson and Heezen (1967) which stated that the ridge was a continental fragment detached from Greenland when the active sea-floor spreading axis shifted west from the centre of the Norwegian Basin. Leading from this hypothesis, they suggested that the Norwegian Basin is between 100 and 200 M.y. old, a suggestion refuted by Vogt et. al. (1970b) who showed that the Basin started to develop about 60 M.y. ago. Vogt et. al. (1970b) also pointed out the similarity of the region to the Arctic Ocean, where the Alpha Ridge may be an extinct spreading axis. The transition from Norwegian Basin onto the Jan Mayen Ridge is marked by a steep bathymetric rise that exhibits a remarkable north-south trend. The southern section of the ridge is much less pronounced than the northern section, and it is not known whether the ridge continues as a buried feature as far south as the Iceland-Faeroe Ridge.

1.3 Evolution of the North Atlantic Ocean and the Norwegian-Greenland Sea.

Since the development of the theory of sea-floor spreading in the early and mid 1960's much research has been carried out into the origin and development of the North Atlantic. However it is still not possible to give a detailed evolutionary history which will explain all of the observed phenomena. It is known that most of the opening north of the Charlie Gibbs Fracture Zone has taken place within the last 60 M.y., but the events that led up to the final rifting of Greenland and Eurasia are thought to date back much further.

The North Sea has been an area of subsidence since the late Palaeozoic or early Mesozoic and it has been suggested (Gibb and Kanaris-Sotiriou, 1976) that the Jurassic igneous rocks found in the Forties (oilfield) region were created by a proto-spreading axis (or the cause thereof) that extended due north from the Azores at least until the Middle Jurassic. According to this theory the tectonic activity along the postulated axis was sufficient to produce an east-west tensional regime and consequent crustal thinning beneath the North Sea, but insufficient to cause a complete rifting of the crust. The spreading axis is then postulated to have migrated westward at about Cretaceous time, leaving the North Sea to continue gently subsiding.

The early spreading history of the northern North Atlantic is difficult to establish with certainty, but it appears that the opening between the Grand Banks and Iberia occurred in the early Cretaceous. It is generally accepted that the Rockall Trough did open by sea-floor spreading during the Cretaceous (eg Scrutton and Roberts, 1971; Pitman and Talwani, 1972), although Russell (1976) has suggested a Permian opening. It is probable that the Faeroe-Shetland Channel was created at the same time as a northward continuation of the Rockall Trough. A fit of the bathymetric contours on either side of the Trough can be made by rotating the Rockall microcontinent by 2.7^{o} about a pole at 76^{o}N, 90^{o}E (Bott, 1978). There were no conspicuous geomagnetic reversals between 85 and 110 M.y. ago (Larson and Pitman, 1972) so that sea-floor spreading in the Rockall Trough and Faeroe-Shetland Channel during this period would not create the characteristic linear magnetic anomalies.

Spreading about a northwest-southeast axis in the Labrador Sea was initiated about 80 M.y. ago (Laughton, 1975), coincident with the cessation of spreading in the Rockall Trough (Srivastava, 1978). The Labrador Sea first opened in the south at about anomaly 32 time, and later in the north at about anomaly 28 time. Active spreading in the Norwegian-Greenland Sea and between Rockall and Greenland commenced just before anomaly 24 time (Vogt and Avery, 1974), although it has been suggested that there had been some crustal stretching and thinning as far back as anomaly 32 time (Srivastava, 1978). The development of sea-floor spreading in the Norwegian Sea and along the proto Reykjanes Ridge created a triple rift junction southeast of Greenland (Laughton, 1975; Kristoffersen and Talwani, 1977), and also brought about a change in the direction of spreading within the Labrador Sea. Anomaly 24 has been identified on either side of the Mohns Ridge as far north as the Greenland and Senja Fracture zones. Further north the movement between Greenland and Eurasia took the form of shearing along what has since become the Knipovich Ridge.

The change in the spreading direction in the Labrador Sea caused the opening of the Davis Strait and Baffin Bay. The massive lava flows of the Brito-Arctic province date from about this time (Tarling and Gale, 1968) and it is reasonable to presume that they are also related to this major splitting event.

With the commencement of spreading about the Reykjanes Ridge the Rockall microcontinent began to subside. Evidence from D.S.D.P. holes 116 and 117 (Laughton, Berggren et. al., 1972) shows that the Hatton-Rockall Basin subsided 1200 m between 55 and 50 M.y. ago. At the same time Orphan Knoll subsided by 1800 m even though it was not close to the new split. As Eurasia and Greenland moved apart, the Iceland-Faeroe Ridge grew as a result of the outpouring of subaerial basalts concurrent with sea-floor spreading to the north and south. At about the latitude of the Iceland-Faeroe Ridge the spreading axis was offset between the Norwegian Sea and the Reykjanes Basin.

Spreading continued with three-plate motion until about Upper Eocene, when the opening of the Labrador Sea ceased and Greenland became part of the North American plate. The implicit change in the direction of plate motion that this caused is believed to be the reason for the different azimuths of the two sections of the Jan Mayen Fracture zone (Talwani and Eldholm, 1977), the younger section of the fracture zone having a trend of east-west as opposed to the northwest-southeast trend of the older section. North of the Iceland-Faeroe Ridge spreading continued, but the fan-shaped magnetic anomaly pattern indicates that the spreading history here is more complex than further south. It is difficult to identify anomalies younger than anomaly 19 in the Norwegian Basin, but spreading within the basin is not thought to have ceased until about anomaly 7 time (Talwani and Eldholm, 1977). Johnson et. al. (1972) suggest that the spreading ceased about 30 M.y. ago. At sometime between anomaly 13 and anomaly 7 the Knipovich

Ridge began to act as a spreading rift, separating Greenland from the Svalbard block, thereby breaking the de Geer land bridge between Europe and North America.

Following the extinction of the Norwegian Basin axis, the spreading axis shifted west to a position beneath the present Icelandic Plateau, splitting the Jan Mayen Ridge away from Greenland (Johnson and Heezen, 1967). Spreading about this new axis took place from anomaly 6C time until anomaly 5D time (Talwani and Udintsev, 1976) when the spreading axis again jumped westward to take up its present position. Between the Jan Mayen Fracture Zone and the Greenland-Senja Fracture Zone sea-floor spreading has continued without significant interruption since the initial rifting, and it seems that the Mohns Ridge has always had a central location between the two continents.

In order to explain some of the peculiarities of the region variations on the "hot-spot" ideas of Wilson (1963) have been produced and it has been postulated (Morgan, 1971; Schilling and Noe-Nygaard, 1974) that a mantle plume was active beneath the region at some stage in its evolution. This, it is argued, would account for the presence of the localized areas of unusual elevation. However, as pointed out by Talwani and Eldholm (1977), the behaviour of such a plume would need to be highly erratic, and the plume capable of random motion if such an explanation were to account for all of the unusual features of the area. Bott (1973) suggested that a convective overturn of the mantle of relatively short duration could be the cause of the unusual features. This theory has the advantage that if the overturn occurred beneath the whole region displaying volcanism, the wide lateral extent of the activity can be easily understood. Moreover, this theory suggests a once-and-for-all situation, more akin to the observed phenomena than the mantle plume idea or the ideas of Talwani and

Eldholm (1977), who postulate a huge "hot-spot" that is supposed to have underlain the region since before rifting and which, they claim, is still in existence at the present time.

The most recent major tectonic event has been the evolution of Iceland within the last 20 M.y. (Moorbath et. al., 1968). There is apparently an anomalous upper mantle beneath Iceland, with a seismic velocity of 7.4 km/s, extending down to about 150 - 200 km (Tryggvason, 1962, 1964). The bowl-like Bouguer anomalies over Iceland indicate that it is in approximate isostatic equilibrium, in common with the Iceland-Faeroe Ridge.

1.4 The aims of this project.

This project was designed to investigate the structural framework of the continental margin between Norway and the Norwegian Basin. The evolutionary history of this region is unclear and it was hoped that the data gathered on the two cruises would provide new evidence as to the time and method of the area's development. In particular, the project was designed to try to unravel the early Tertiary history of the region by accurately delineating the boundary between the continental and the oceanic material (ie the location of the Tertiary rift between Greenland and Eurasia), and by positively identifying the oldest linear magnetic anomalies within the Norwegian Basin. It was further hoped that some indication of the pre-Tertiary evolution of the region could be found.

Chapter 2

Data Acquisition and Processing

2.1 Introduction

The R.R.S. Shackleton sailed from Barry, South Wales, on the 3rd September 1976 to start cruise 4/76. It had been planned to start the cruise on 1st September, but late delivery of the vessel from the ship-repairers, combined with delays in the loading of equipment at Barry, resulted in a two day reduction in the cruise programme. Bad weather and equipment problems on route to the Shetland Isles cut the time available for the first leg of the survey to seven days. Four northwest-southeast traverses of the continental margin were completed before the ship returned to Lerwick, as shown in figure 1.1. The second half of the cruise consisted of a survey over the Rockall-Faeroe microcontinent, but this half of the cruise was hampered by deteriorating weather conditions which eventually forced its abandonment. The ship then returned to Barry, docking on the 29th September.

A further traverse of the continental margin was undertaken during August 1977 as part of the second leg of the Shackleton cruise 9/77. The traverse extended across the entire Norwegian Basin and filled a gap in the coverage obtained during the 1976 cruise. The ship's track is shown in figure 1.1.

2.2 Equipment.

Two complementary data collection and storage systems were used throughout both cruises. A modified Decca data-logger, provided by the Institute of Oceanographic Sciences, was used to continuously record gravity, magnetic, bathymetric and some navigational data onto 9-Track digital magnetic tapes which were subsquently processed by the shipboard computer unit. A separate Digital Field System, provided by Durham University, was used to record continuous seismic reflection data, and, whenever necessary, seismic refraction data. All seismic data was recorded onto 9-Track digital magnetic tape for subsequent processing in Durham.

2.2.1 Navigation.

Navigation technology has improved greatly during the past 30 years, but there is still no single system capable of continuous position-fixing to within 100 m in oceanic waters. Consequently a wide variety of navigation equipment was carried by the Shackleton, and all suitable methods of position-fixing used.

The primary navigation aid used on both cruises was a Magnavox 702A Satellite Navigation System. This system utilizes signals transmitted by U.S. Navy satellites in orbit around the earth, and by measuring the Doppler shift of the signals as the satellites pass overhead it is capable of very high accuracy. Calculations were performed on a Hewlett Packard HP2100A computer by a N.A.T.O. program. Only half of the computer's memory was functioning during the 1976 cruise, necessitating the use of a slightly less sophisticated computer program. Calculated positions were displayed in the laboratory on a Teletype ASR 33 terminal and upon the ship's bridge on a Texas Instruments "Silent 700" terminal. The overall performance of the system was very good, with only an occasional break-down.

Satellite navigation is capable of giving the ship's position to within 100 m in good conditions. In order to achieve reasonable accuracy, the maximum elevation of the satellite above the horizon should be between 10° and 80°, while for maximum accuracy it must be between 20° and 60°. The six satellites in the system provide sightings at approximately 90 minute intervals, although at high latitudes many of these sightings fall outside the desired elevation range. Moreover, it was found that if a second satellite should appear over the horizon while the system was already tracking another, then interference between the signals frequently caused spurious results. Manual selection of the sightings used proved to be an excellent method of filtering out spurious fixes. The length of time between accurate fixes is the major drawback of this system, so alternative techniques, updated at each accurate satellite fix, were used to calculate the ship's position on a continuous basis.

Continuous position information was provided by a Loran C System. This is a hyperbolic radio system, similar to the Decca Navigator, which operates on a single frequency of 100 KHz. The ship's position is calculated by measuring the time differences between a signal arriving from a master transmitter and two signals arriving from slave stations.

The great advantage of the Loran C system, compared to the satellite navigation system, is that it is continuous. Moreover, in good conditions it is capable of the same order of accuracy as the satellite navigator. However, it suffers a major problem in that the signal transmitted forms two waves, a ground-wave travelling along the surface of the earth and a sky-wave which travels up into the ionosphere and is reflected back down. All measurements are made using the ground-wave but the sky-wave can produce interference, especially at night, causing the receiver to generate spurious results. Good quality results were obtained from the system during day time, but little use was made of the results obtained at night. A Decca DL 91 receiver was used and the output was recorded on the data-logger and also by the watch-keepers at 10 minute intervals.

Dead-reckoning was used to supplement the satellite navigation whenever the Loran was unreliable or unserviceable. Velocity information was derived from the ship's E-M Log and heading information from the gyrocompass. Both instruments were connected to the data-logger for automatic recording.

2.2.2 Magnetic measurements.

Magnetic data was obtained by a Varian V4937 magnetometer using a proton-precession sensor towed 200 m behind the ship at a depth of 7-10 m. At this distance it is believed that the magnetic signature of the ship is negligible. Signals from the sensor were processed and displayed by the Varian and were also displayed on a chart recorder. The system has a sensitivity of 1 gamma and is accurate to ± 1 gamma. The chart recorder was annotated every 10 minutes by the watch-keepers and the output of the magnetometer recorded by the data-logger. No problems were experienced with this equipment on either cruise.

2.2.3 Gravity data.

A La-Coste and Romberg shipboard gravity meter, serial number S40, was used on both cruises. The output was recorded on the data-logger which recorded gravity value and spring tension, and on a drum printer in the laboratory which printed these values every five minutes. In addition, gravity, spring tension, cross-coupling and total correction were displayed on a chart recorder in the gravimeter room.

The gravimeter functioned well in 1977 but suffered problems during the 1976 cruise. It was unserviceable for 12 hours during part of line 4/76C because of a failure in the beam-damping network. It was also found that the connections between the data-logger (in the laboratory) and the gravimeter (in the ship's hold) were crossed, so that the logger recorded spring tension for gravity and vice versa. This fault was not discovered until after the completion of the cruise and it necessitated the reprocessing of all of the gravity data.

2.2.4 Bathymetry.

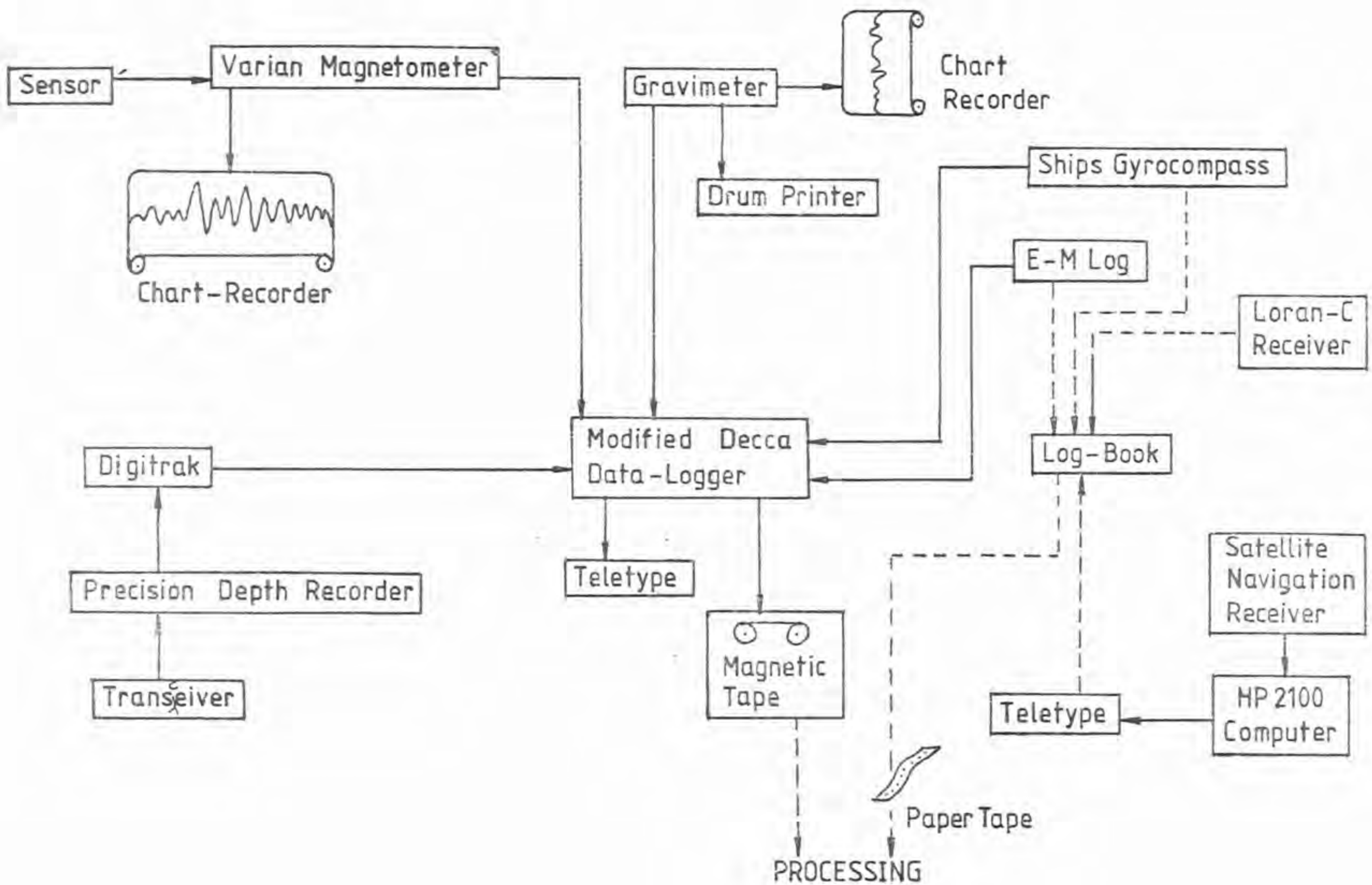
Two independent depth sensors were carried, one mounted on the ship's hull, the other aboard an Edo-Western sonde towed alongside the ship. Signals from the sonde were used in preference to those from the hull as they were far less prone to wave noise. Incoming signals were displayed on two Mufax MS.38 Precision Depth Recorders (P.D.R.) and were then fed into an Edo-Western Model 261C Digitrak for digitization. The digitrak output was recorded by the data-logger and was also displayed in digital form. The system performed well except for depths of around 800 fathoms (1500 metres) and multiples thereof. At these depths the transceiver is transmitting at approximately the same time as the returning echo from the previous transmission arrives back at the sensor. This frequently caused erroneous values to be generated. A gating device on the system helped to reduce this effect but was unable to suppress it totally. Any spurious depths that were recorded were removed during later processing of the data-logger tapes.

A diagram of the non-seismic data acquisition hardware is given in figure 2.1.

2.2.5 Seismic data.

Continous seismic reflection profiling was carried out on both cruises. In addition, wide-angle seismic reflection and refraction

Figure 2.1 The non-seismic data acquisition system used on both cruises.



Sensor
Varian Magnetometer
Chart-Recorder
Gravimeter
Chart Recorder
Drum Printer
Ships Gyrocompass
E-M Log
Loran-C Receiver
Modified Decca Data-Logger
Log-Book
Digitrak
Teletype
Precision Depth Recorder
Magnetic Tape
Satellite Navigation Receiver
Transeiver
HP 2100 Computer
Teletype
Paper Tape
PROCESSING

experiments were undertaken at several locations using disposable sonobuoys. An S.D.S. 1010 Digital Field System (D.F.S.) was used as a system controller for all of the seismic work, whilst airguns were used to generate the seismic energy. It proved to be impossible to use an array of airguns, as had been planned, because of the instability of the sledge carrying the guns. Consequently only a single 300 cu. in. airgun was used during 1976 cruise, and while this gave adequate results, it produced neither the penetration nor the resolution of the planned array. During the 1977 cruise the 300 cu. in. gun was supplemented by two 160 cu. in. guns, resulting in an improvement in the data quality.

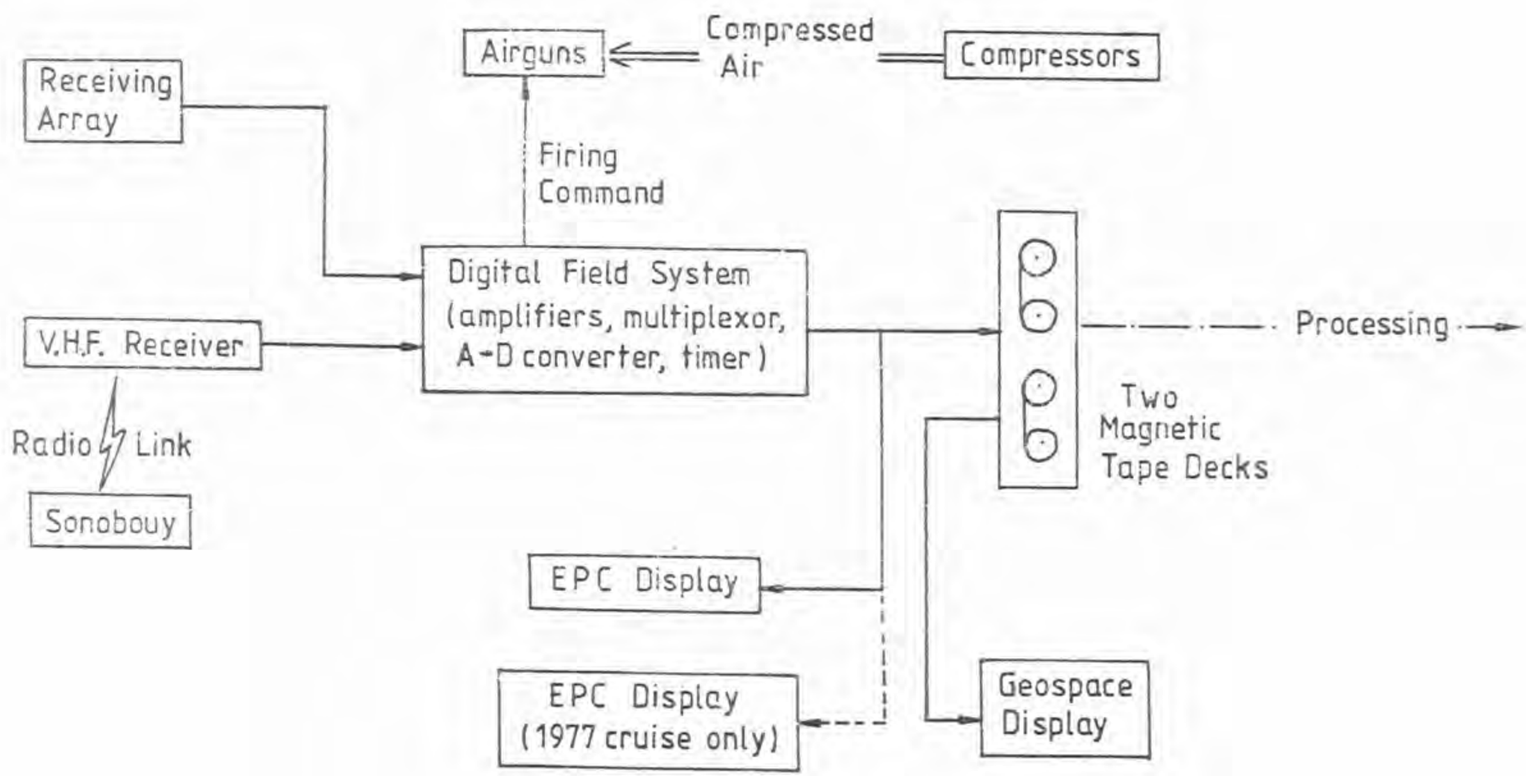
The receiver consisted of a Geomechanique Flexotir array towed behind the ship. The array was formed of 10 active and 10 passive sections, each active section comprising of 50 hydrophones whose outputs were summed, the summed output being treated as a single channel. This arrangement reduced the array's susceptibility to random and wave noise. Eleven active and passive sections were used in the array during the 1977 cruise. The array was towed at a speed of 6-6.5 knots and shots were fired every 17 seconds to allow the records to be Common-Depth-Point stacked at a later date.

Incoming data was multiplexed by the D.F.S. before being fed through a high speed analogue-to-digital converter and recorded onto 9-Track digital magnetic tape. As the D.F.S. is capable of handling up to 24 channels no problems were encountered with recording sonobuoy data in addition to the standard array data. A timing mechanism built into the D.F.S. controlled the shot firing and the operation of the tape decks, ensuring no loss of data. A Geospace MR101A monitor display, operating in a read-after-write mode, allowed the data being recorded to be visually checked. An E.P.C. model 4600 graphic recorder was also used, in a read-before-write mode, to view the profiling record. The black and white, non-photosensitive, display of the E.P.C. device is a great improvement on the pink and blue photosensitive display of the Geospace machine, and has allowedthe profiler records to be reproduced in this thesis. Both machines displayed only 4 seconds of the seismic record, creating gross vertical exaggeration on the E.P.C. display. A second E.P.C. unit was available in 1977 and was used to display the entire record being recorded (typically 7 seconds long).

An E.M.I. Emidata 2500 1 inch, 8-Track analogue tape recorder was taken on both cruises as a back up in case of equipment failure within the D.F.S. but was not used. Several disposable sonobouys were used for refraction and wide-angle reflection work, their hydrophones being set at a depth of 60 ft. Signals picked up by the sonobouys were transmitted to the ship via a V.H.F. radio link and were recorded by the D.F.S. None of the 1976 sonobouy experiments were successful, generally due to an inability to receive the radio signals from the sonobouy. In 1977, however, several of the sonobouys were successfully picked up and useful data recorded.

The 1976 cruise was the first time that a fully digital system had been used at sea by Durham University and it was the first time that the D.F.S. had been used. Problems with parity errors caused one of the tape decks to be abandonned early in the cruise and it was discovered after the cruise that the analogue-to-digital converter had not functioned correctly, applying a large negative D.C. shift to the data. This was not seen on the shipboard monitor displays because the E.P.C. was operating in a read-before-write mode and the Geospace has a built-in automatic gain control that eliminated the effect.

Figure 2.2 The seismic data acquisition system.


Receiving Array
Airguns
Compressed Air
Compressors
Firing Command
V.H.F. Receiver
Radio Link
Sonobouy
Digital Field System (amplifiers, multiplexor, A-D converter, timer)
Processing
Two Magnetic Tape Decks
EPC Display
EPC Display (1977 cruise only)
Geospace Display

The seismic system worked faultlessly during the 1977 cruise. The layout of the seismic acquisition system in shown in figure 2.2.

2.3 Processing.

2.3.1 Data-Logger tapes.

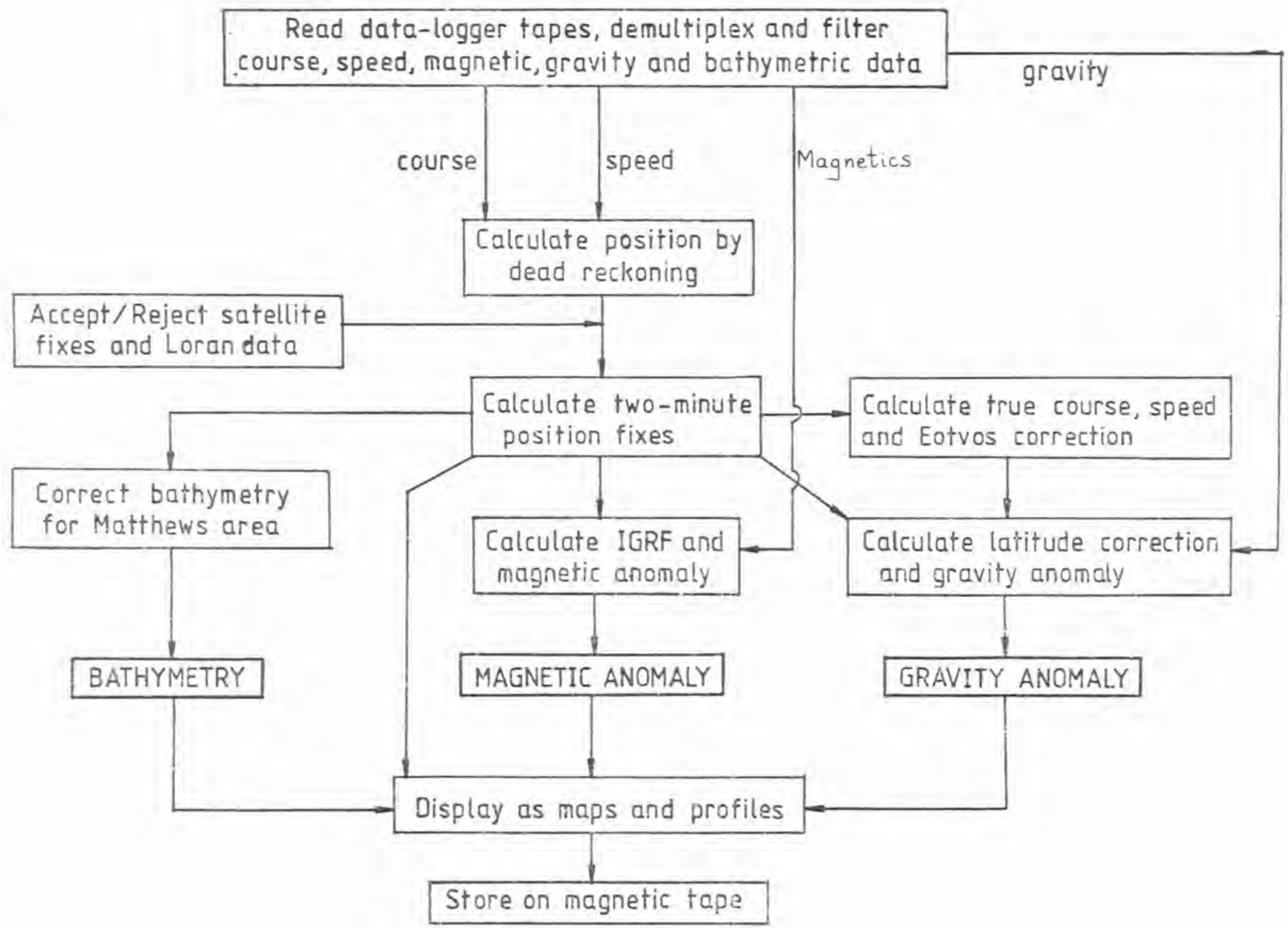
The magnetic, gravity, bathymetric and navigation data recorded by the data-logger were processed by the Shipboard Computer Unit of the Institute of Oceanographic Sciences using a portablecomputer system mounted in a container within the ship's hold. The system consisted of:-

IBM 1131 Central Processor with 8K word memory and
512K word disk drive
IBM 2310 Dual 512K word disk drive
IBM 1133 Multiplexor
Data Dynamics 7200 fixed-head disk
2 R.D.L. 10500 9-Track ½ inch N.R.Z.I. digital tape decks
Tektronix TX4012 V.D.U. and Keyboard
Tektronix 4610-1 Hard Copy Unit
IBM 1627 30 inch drum plotter
Facit paper-tape punch and reader

Figure 2.3 illustrates how the data was processed. Detailed descriptions of the programs used can be found in the Institute of Oceanographic Sciences manuals 1-12 (1974). After processing the data, the system generated final data tapes in accordance with the "Formats for Marine Geophysical Data Exchange" (Anonymous, 1972) which are now stored in Newcastle on the N.U.M.A.C. system. Details of these tapes are to be found in the Appendix.

The magnetic anomaly was calculated using the International Geomagnetic Reference Field (Mead, 1970). No magnetic storms or other

Figure 2.3 Processing sequence for non-seismic data.



Read data-logger tapes, demultiplex and filter course, speed, magnetic, gravity and bathymetric data
course
speed
Magnetics
gravity
Calculate position by dead reckoning
Accept/Reject satellite fixes and Loran data
Calculate two-minute position fixes
Calculate true course, speed and Eotvos correction
Correct bathymetry for Matthews area
Calculate IGRF and magnetic anomaly
Calculate latitude correction and gravity anomaly
BATHYMETRY
MAGNETIC ANOMALY
GRAVITY ANOMALY
Display as maps and profiles
Store on magnetic tape

gross disturbances were detected and no corrections have been applied for daily variations.

The free-air gravity anomaly was derived using the International Gravity Formula (1967). The shipboard gravimeter was tied into base stations at Barry, Lerwick and back at Barry in 1976, and at Reykjavik and Manchester in 1977, using a portable Worden gravimeter. Station ties at the start and end of the 1976 cruise show that the meter had drifted by less than 0.4 mgal during the 27 days of the cruise. During the 1977 cruise the meter drifted by 0.29 mgal. see Appendix

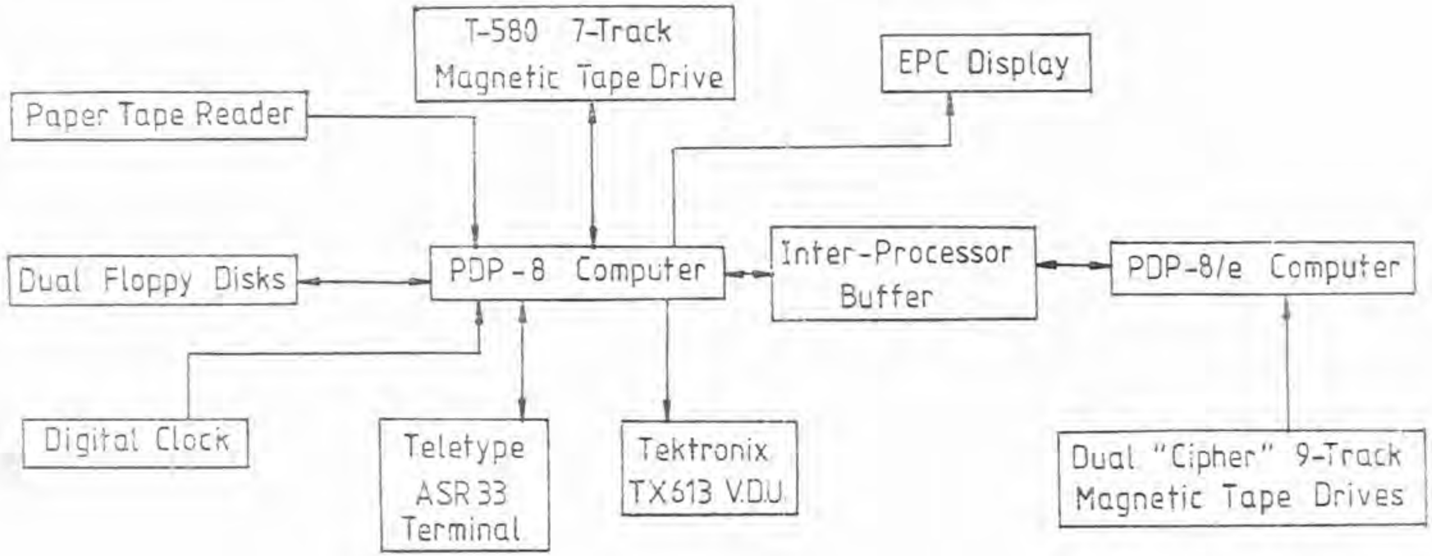
2.3.2 Seismic data processing.

The use of the S.D.S. 1010 system meant that all processing of the seismic data could be carried out digitally and was therefore not subject to time considerations in the manner of analogue data. The processing was limited however by the use of existing low-cost equipment at Durham and only some of the data was processed. The processing system used consists of:-

DEC PDP-8 Computer with 28K word memory
DEC PDP-8/e Computer with 8K word memory
2 Cipher 9-Track, ½ inch digital tape decks
2 Calcomp floppy-disk drives with formatter
DEC T-580 7-Track, ½ inch digital tape deck
EPC Model 4600 graphic recorder
Tektronix TX613-1 V.D.U.
Teletype ASR-33 terminal
Systron-Donner digital clock

The layout of the system is shown in figure 2.4. The DEC OS/8 operating system was used, with additional software provided by Mr. J. H. Peacock, Mr. G. Wylie, Mr. K. Mitchelmore and the author.

Figure 2.4 Layout of the seismic processing system used during the project.


T-580 7-Track Magnetic Tape Drive
EPC Display
Paper Tape Reader
Dual Floppy Disks
PDP-8 Computer
Inter-Processor Buffer
PDP-8/e Computer
Digital Clock
Teletype ASR 33 Terminal
Tektronix TX613 V.D.U.
Dual "Cipher" 9-Track Magnetic Tape Drives

Great problems were experienced whilst attempting to use this system. For a large portion of the project the hardware was incomplete, and when it was complete, operational reliability was poor. Moreover, the slow execution speed of the PDP-8 coupled with its small data capacity severely limited the amount of processing that it was feasible to undertake. Common-Depth-Point stacking is not feasible on the system due to the time that such an operation would require.

Processing has therefore been carried out for a few selected sections of the profiles. Elsewhere the interpretation has depended on the shipboard-monitor records. Processing consisted of performing a near-trace gather, ie summing the first four channels, and subjecting the result to a fast Fourier transform and band-pass filter package developed by Mr. K. Mitchelmore. This was followed by an inverse Fourier transform and an automatic gain control (A.G.C.) routine developed by the author and Mr J. H. Peacock. Finally the result was displayed in variable area format using software developed by the author. The response of the A.G.C. is shown in figure 2.5.

A dramatic improvement in the quality and clarity of the seismic sections was achieved even with this limited processing. The signal-to-noise ratio was increased by a factor of 2 by the near-trace gather; the variable area display reduced the vertical exaggerations by a factor of 12; and the band-pass filtering removed the low-frequency noise of the ship's engines, the high frequency wave noise and also removed the D.C. shift from the 1976 records. The improvement produced by the processing is illustrated in figure 2.6 which shows a section of a profile before and after processing.

Figure 2.5 The response of the Automatic Gain Control function applied to the data during processing.

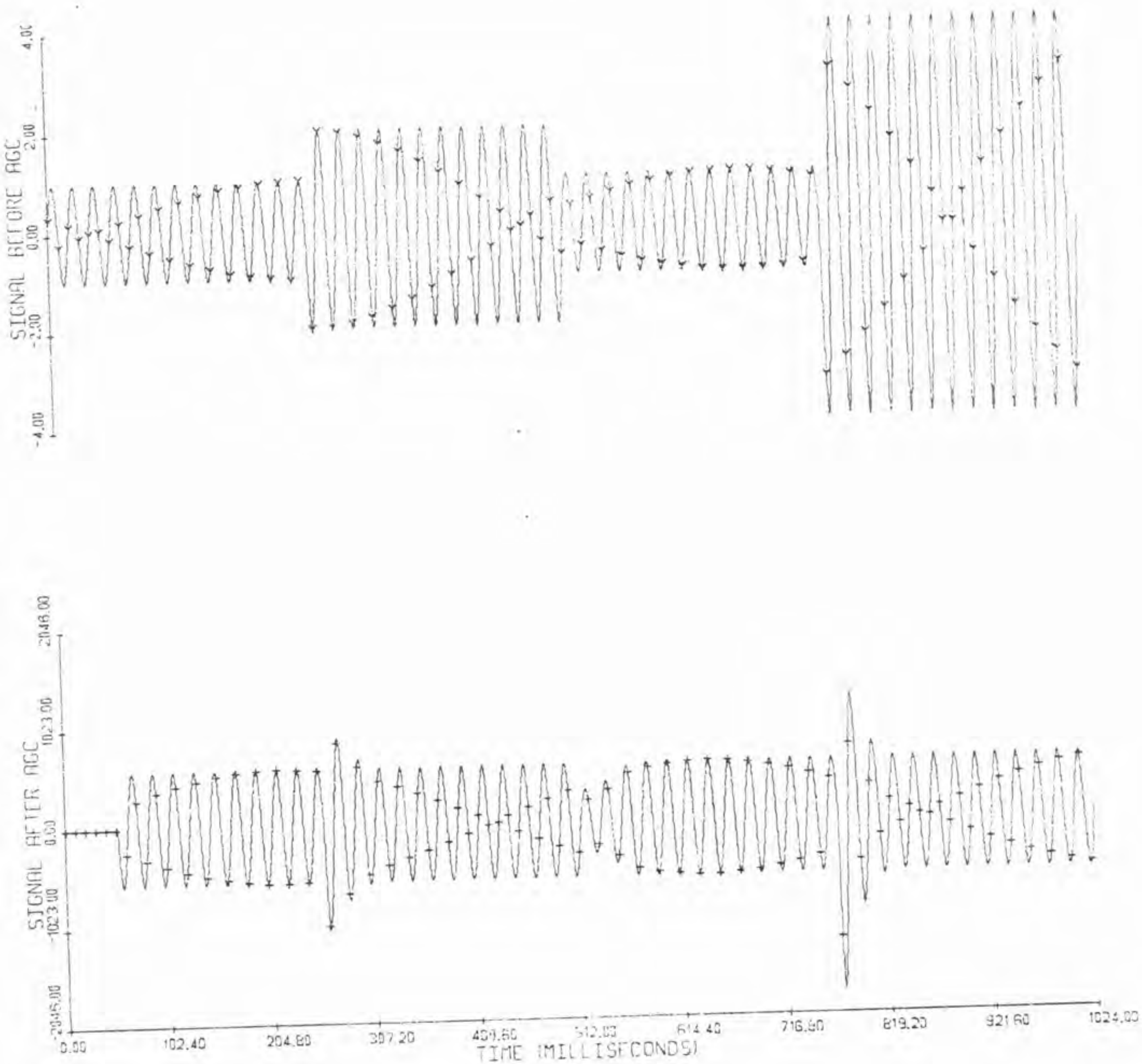
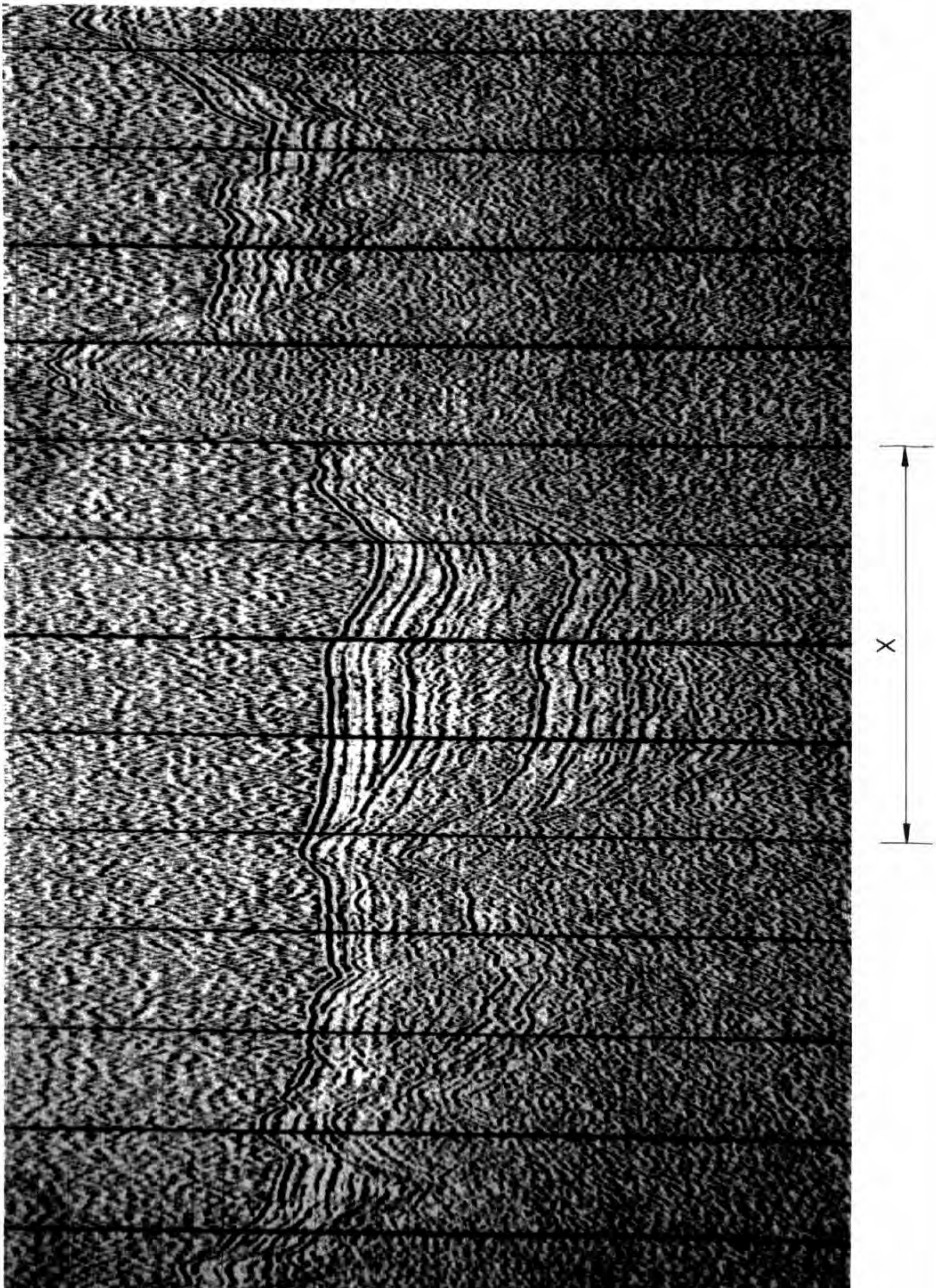
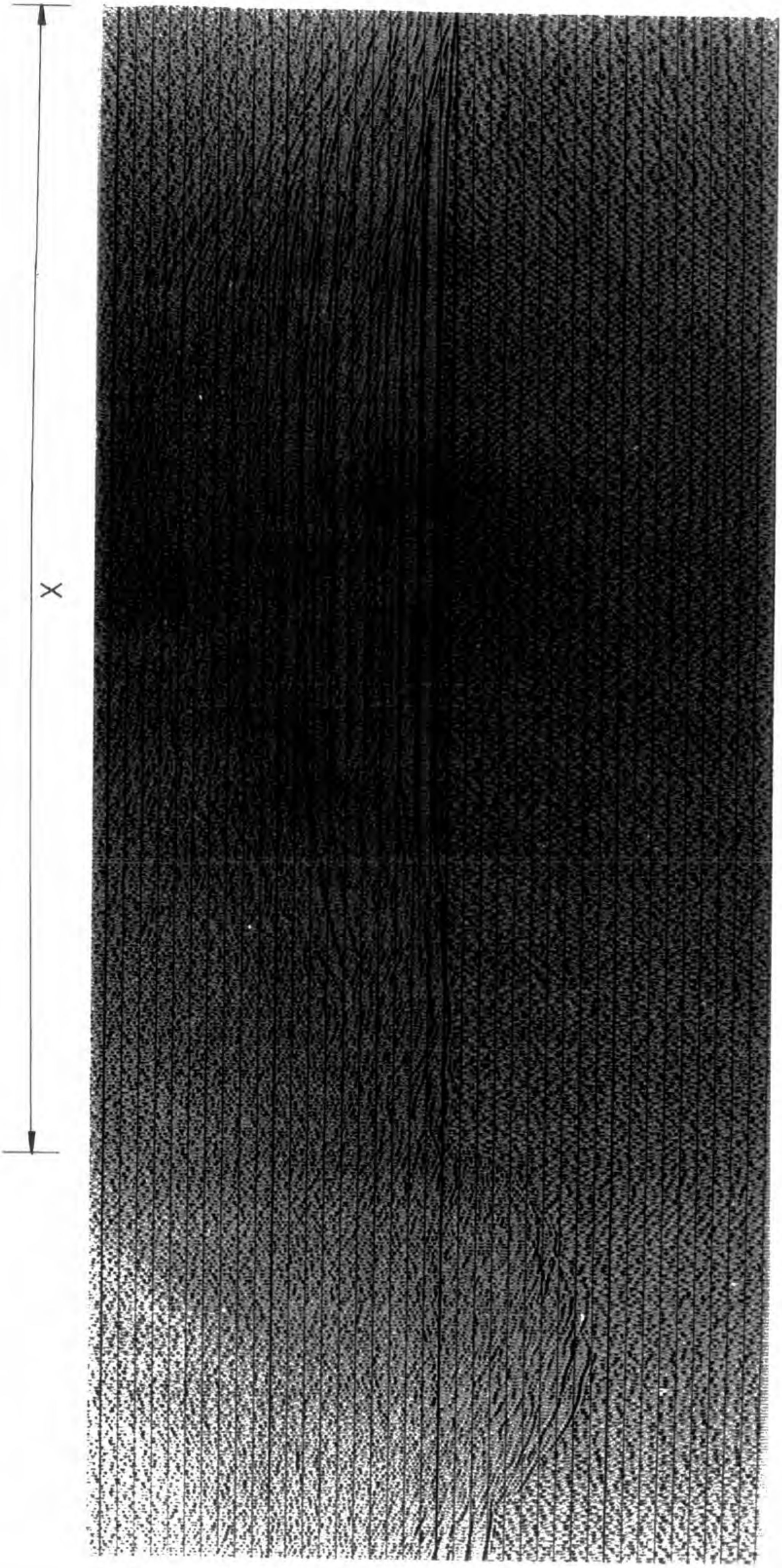

SIGNAL BEFORE AGC
4.00
2.00
0.00
-2.00
-4.00
SIGNAL AFTER AGC
2046.00
1023.00
0.00
-1023.00
-2046.00
0.00
102.40
204.80
307.20
409.60
512.00
614.40
716.80
819.20
921.60
1024.00
TIME (MILLISECONDS)

Figure 2.6 An illustration of the improvement in data quality produced by the processing of the seismic data.
The photographs show the same part of line 9/77R before and after processing, with the same distance indicated by the letter X.


X


X

Chapter 3

The continental margin of the eastern Norwegian Basin

3.1 Introduction.

The work of Talwani and Eldholm (1972, 1974, 1977) has brought about a much greater understanding of the structure and evolution of the Norwegian-Greenland Sea. However, there are difficulties with their interpretation of the data from the eastern and southeastern margins of the Norwegian Basin, especially in the region around the Faeroe Isles. These difficulties arise out of their belief that the Faeroe-Shetland Escarpment marks the continent-ocean boundary in this area and that the Faeroes Block is oceanic in origin. Bott et. al. (1974, 1976) have provided evidence that the Faeroes Block may be continental in nature, implying therefore that the Faeroe-Shetland Escarpment does not mark the continent-ocean boundary, at least not in the south. The key to resolving this conflict lies in fully understanding the nature and structure of the basement high detected to the west of the Faeroe-Shetland Escarpment. If the origin of this feature could be unequivocably determined then much greater constraints could be applied to the origins of the region to the south. It may also be possible to infer the origins of the Faeroe-Shetland Channel if the nature of the basement high is known. Thus this study has concentrated on the eastern margin of the Norwegian Basin to try to resolve these questions.

In the following account the lines undertaken by Durham are identified by cruise number, year and line letter, eg line 4/76B refers to line B of the 4th Shackleton cruise in 1976. Data from cruises undertaken by the Lamont-Doherty Geological Observatory e.g. Figures 3.6, 3.7, 3.9, 3.12 has been used in addition to the data gathered by Durham, and this data is denoted by the letter "V" followed by cruise number and leg number, eg V2803 refers to the third leg of the 28th cruise of the R.V. Vema. A particular position along a track is denoted by a notation such as 259/1000 which refers to the ship's position at 1000 GMT on Julian Day 259.

3.2 Seismic and Bathymetric data.

Continuous multi-channel seismic reflection profiling was carried out along four northwest-southeast traverses of the continental margin during the 1976 cruise and along a single northwest-southeast traverse across the entire Norwegian Basin and margin during the 1977 cruise. A shortage of magnetic tapes prevented profiling along the "dog-legs" between the traverses. The shipboard seismic monitors were capable of displaying only four seconds of each record (typically seven seconds long) so the zero datum on the displays was adjusted whenever necessary to ensure that the correct part of the record was displayed. This process resulted in discontinuities on the displays which, when combined with other effects eg multiples, radio transmissions etc, has meant that the raw seismic records are generally unsuitable for reproduction in this thesis. In exceptional circumstances, where the record is sufficiently clear, the raw data is shown, but normally only line drawings of the records are presented. All reflection times used in the text and diagrams refer to two-way travel time unless stated otherwise. Line drawings of the seismic and bathymetric profiles are shown in figures 3.1(a)-(e).

The seismic profile along line 4/76B is typical in many ways of the traverses across the margin and illustrates most of the salient features of the area. To the west, in the Norwegian Basin, a reasonably smooth sea-bed is underlain by between 1.0 and 1.5 seconds of sediments. Beneath the sediments the acoustic basement is formed

Figure 3.1 (a) Seismic reflection profile along line 4/76A.

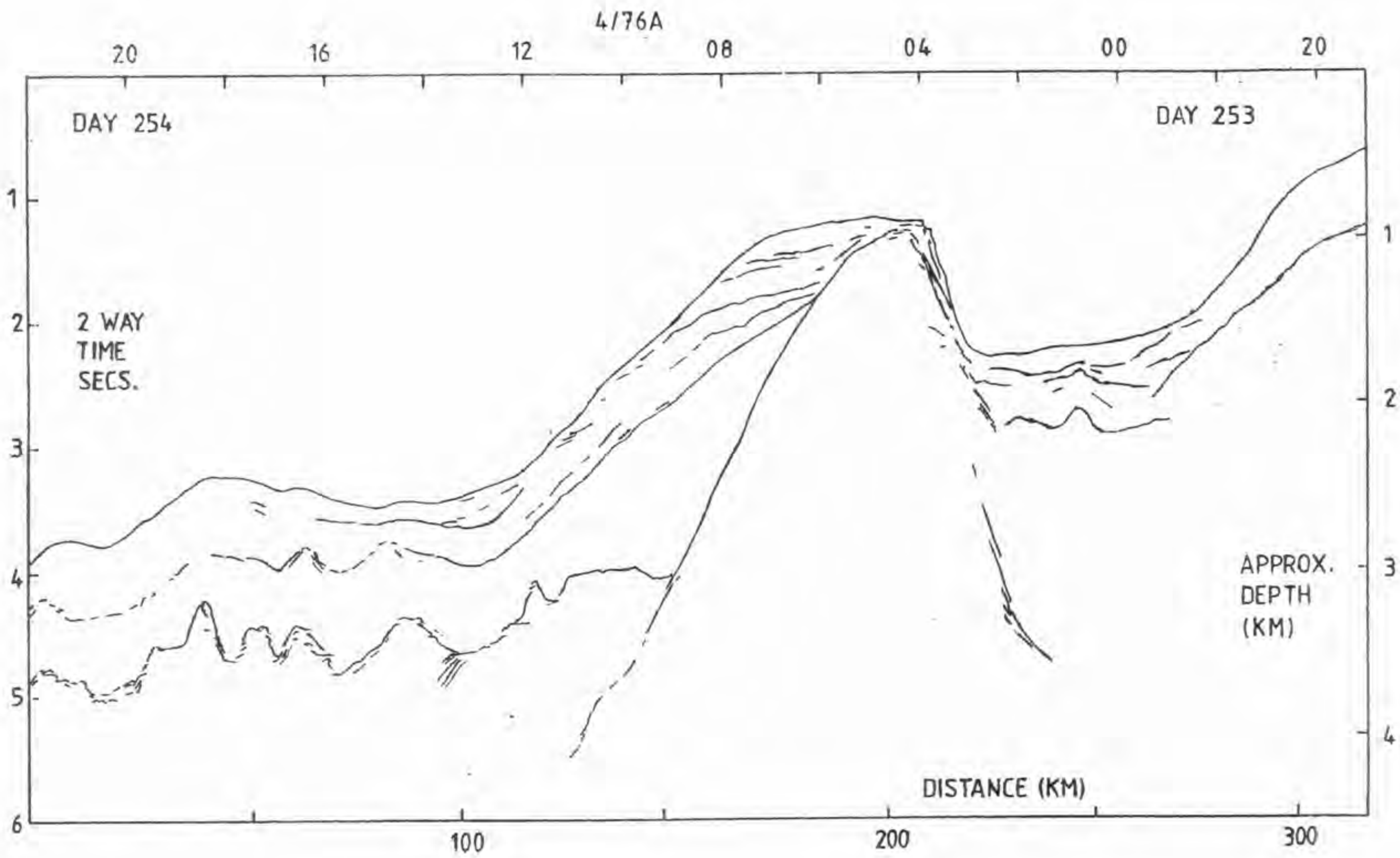
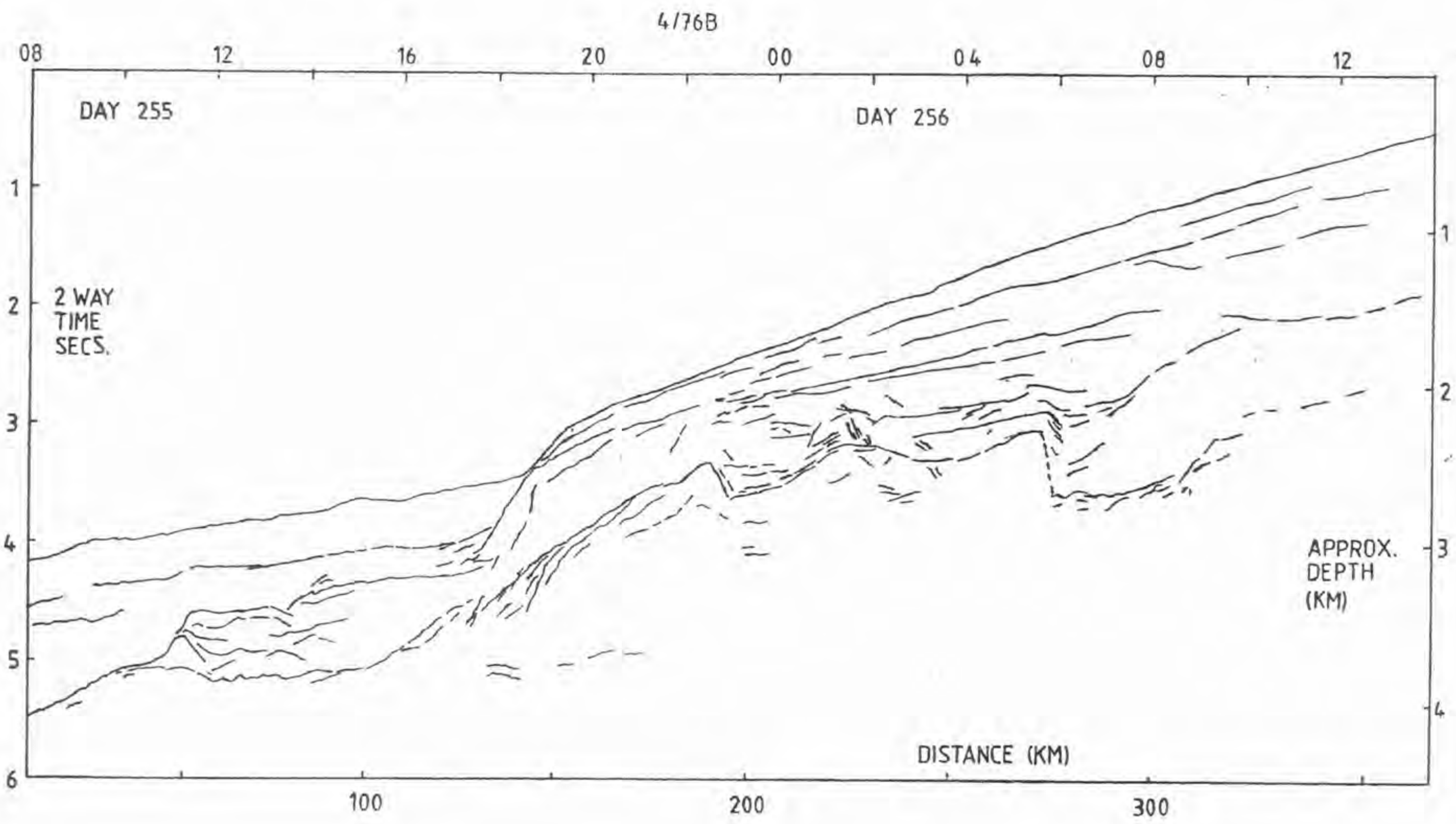

4/76A
20
16
12
08
04
00
20
DAY 254
DAY 253
1
2
3
4
5
6
2 WAY
TIME
SECS.
APPROX.
DEPTH
(KM)
DISTANCE (KM)
100
200
300

Figure 3.1 (b) Seismic reflection profile along line 4/76B.



4/76B
08
12
16
20
00
04
08
12
DAY 255
DAY 256
2 WAY
TIME
SECS.
1
2
3
4
5
6
APPROX.
DEPTH
(KM)
1
2
3
4
100
200
300
DISTANCE (KM)

Figure 3.1 (c) Seismic reflection profile along line 4/76C.

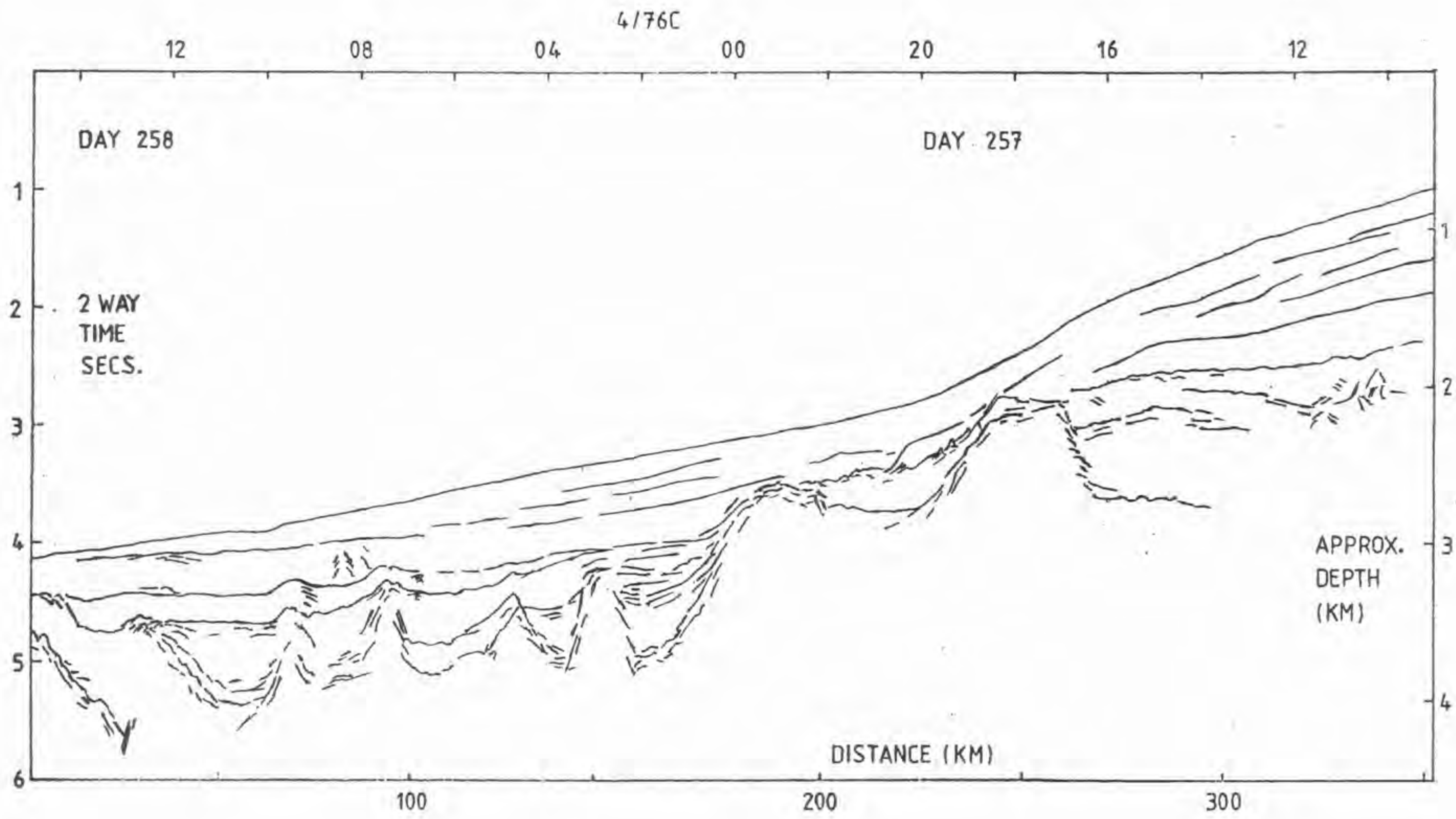

4/76C
12
08
04
00
20
16
12
DAY 258
DAY 257
2 WAY
TIME
SECS.
1
2
3
4
5
6
APPROX.
DEPTH
(KM)
1
2
3
4
DISTANCE (KM)
100
200
300

Figure 3.1 (d) Seismic reflection profile along line 9/77R.

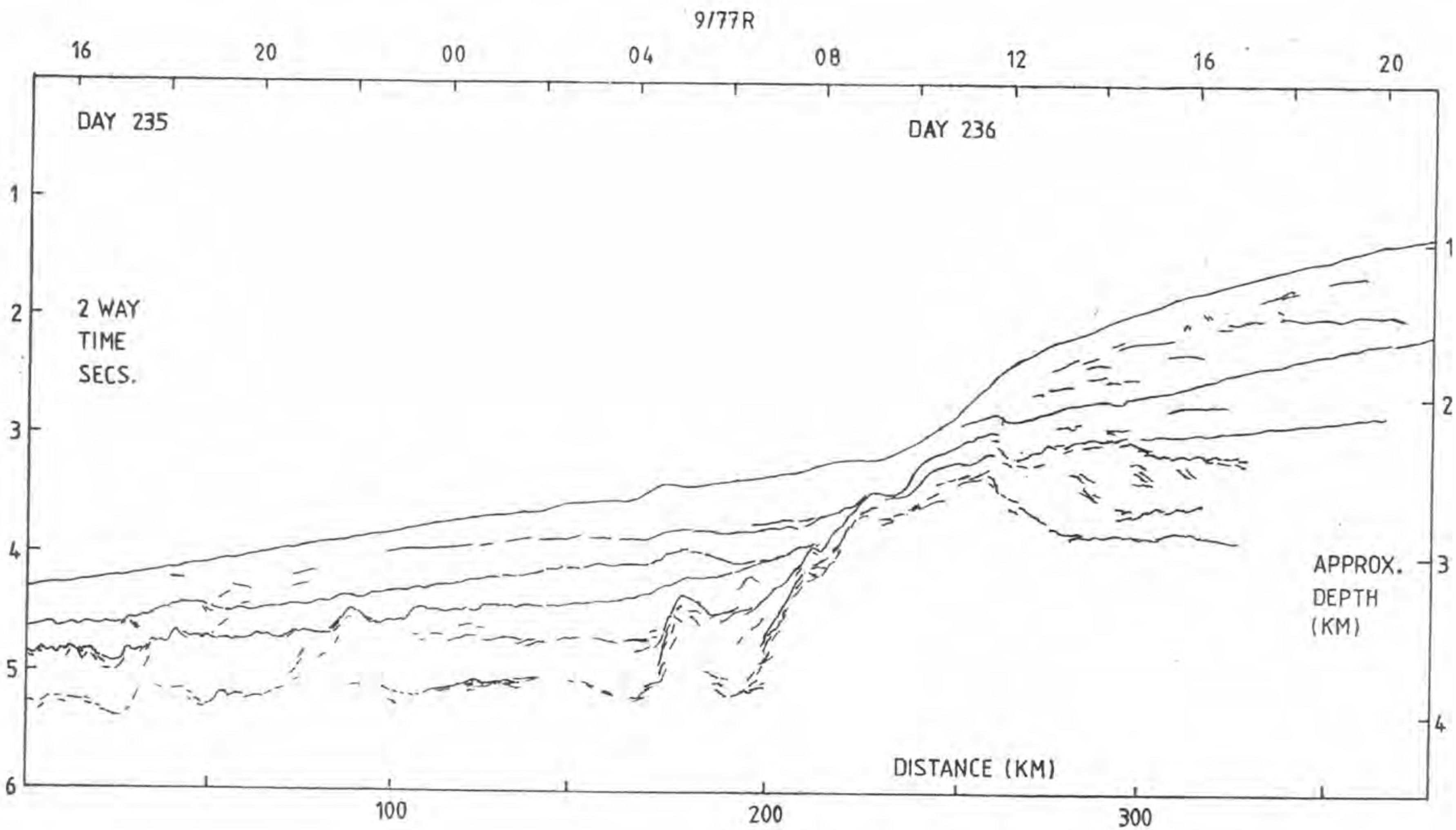
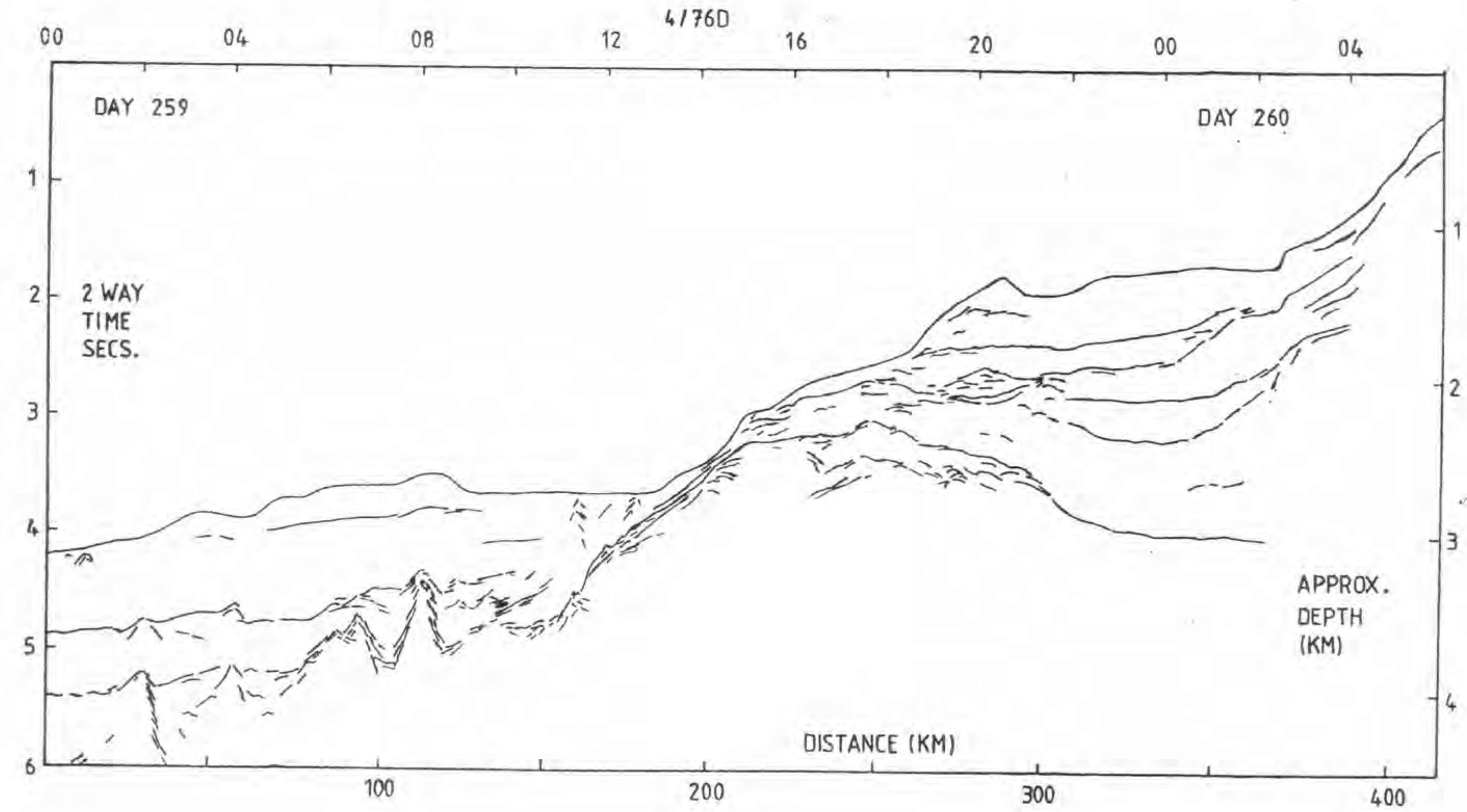

9/77R
16
20
00
04
08
12
16
20
DAY 235
DAY 236
2 WAY
TIME
SECS.
1
2
3
4
5
6
APPROX.
DEPTH
(KM)
1
2
3
4
DISTANCE (KM)
100
200
300

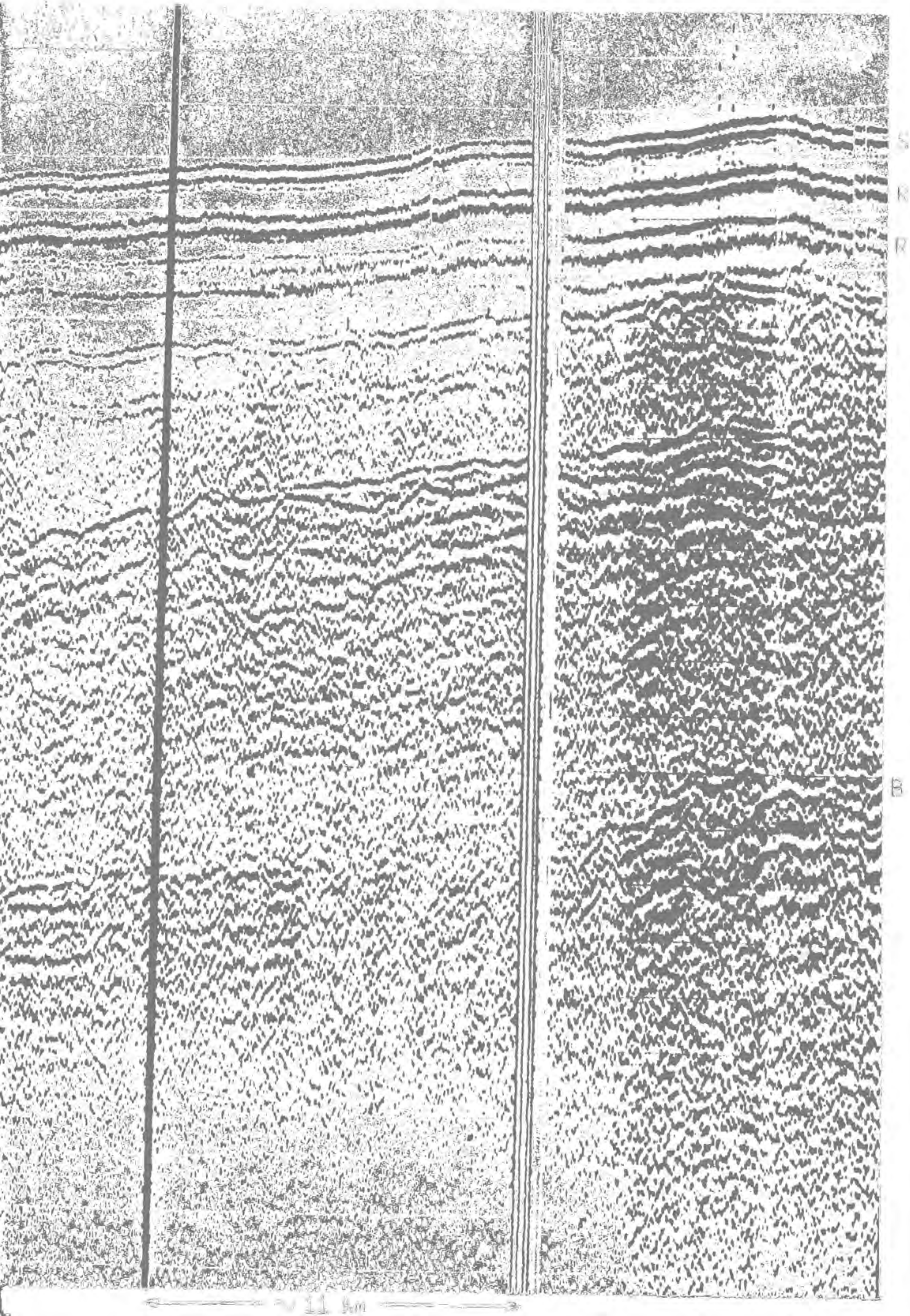
Figure 3.1 (e) Seismic reflection profile along line 4/76D.


4/76D
00
04
08
12
16
20
00
04
DAY 259
DAY 260
2 WAY
TIME
SECS.
1
2
3
4
5
6
APPROX.
DEPTH
(KM)
1
2
3
4
DISTANCE (KM)
100
200
300
400

by a layer which exhibits the typically rough topography of oceanic layer 2. An enlarged view of this oceanic structure is shown in figure 3.2. The processed records reveal that the basement is apparently formed of a large number of on-lapping bodies which exhibit some internal layering, and it is the juxtaposition of these bodies which causes the rough surface of the basement and generates the frequent diffraction hyperbolae visible on the raw records. The layer has a high reflectivity and rarely is anything seen beneath it. Not visible on line 4/76B but clearly seen along line 4/76C (figure 3.1(c)) are numerous basement hummocks separated by deep pools of sediments. It is not possible to correlate the hummocks between profiles, so these appear to be purely local structures.

There is a gentle transition from the deep oceanic basin onto an extensive continental rise with a slope of between 0.3^{o} and 0.5^{o}. Beneath the lower continental rise the basement rises steeply to form a broad structural high, but while the sediment cover over the high is thin, there is no direct bathymetric expression of the feature visible on any of the profiles. The sediment cover over the high becomes progressively thinner to the north, decreasing from a thickness of approximately 0.75 seconds on line 4/76B to less than 0.2 seconds on line 4/76D. The eastern boundary of the high is formed by the east-facing Faeroe-Shetland Escarpment, where the acoustic basement drops steeply to the east. The escarpment is clearly seen on lines 4/76B and 4/76C (figures 3.1(b), (c)) but was not detected further north along lines 9/77R and 4/76D. On these lines the basement was seen to disappear eastwards beneath an increasing thickness of sediments. To the east of the structural high is a deep sedimentary basin stretching almost as far as the Norwegian coast. Some stratification of the sediments is visible within the basin but the

Figure 3.2 An enlarged view of the seismic section from profile 4/76B showing the oceanic structure of the Norwegian Basin.
The basement (B) is overlain by a layer approx. 0.7 seconds thick, the top of which forms a good seismic reflector. Above this is about 0.6 seconds of sediment up to the sea-bed(S). This section shows a good example of the airgun ringing which plagued the survey. Reflectors marked R are ghosts of the sea-bed caused by the airgun bubble not collapsing immediately but oscillating instead. This ringing affects all reflectors, not merely the sea-bed. The thick, vertical black lines are hourly timing lines & the thin horizonal black lines are 100mS timing lines.


S
K
R
B
~ 11 km

resolution of the seismic system is insufficient to reveal the detailed sediment structure, although this would be greatly improved by comprehensive processing of the data. The water depth above the basin is less than 500 m so the deeper reflectors are masked by strong sea-bed multiples. The base of the sediment pile was not detected on any of the profiles.

A different sequence of structures was observed along line 4/76A (figure 3.1(a)), because unlike the other profiles this line crossed the northeastern extensions of the Faeroes Block and the Faeroe-Shetland Channel. The oceanic structure of the southeastern Norwegian Basin, as observed along this line, is similar to that found further north. However, along this line the acoustic basement beneath the basin is seen to abut onto the deep structure of the Faeroes block, as shown in figure 3.3, rather than onto the basement high seen to the north. The sea-bed rises over the Faeroes Block and the sediment cover decreases, so that the basement outcrops on the sea-bed for a short distance near to the eastern edge of the block. To the east of the outcrop the basement and sea-bed drop steeply eastwards, forming the western boundary of the Faeroe-Shetland Channel, as illustrated in figure 3.4. The sediments within the channel are unusually transparent and homogeneous, as clearly shown in figure 3.4 where the basement is visible beneath approximately 2-3 seconds of sediments. The sediments display little internal layering, but some structure is present within the sediments. Several hummocky structures were detected within the channel, with the deeper layers of these structures exhibiting the greatest amount of folding. One such structure is visible in figure 3.4. No gravity or magnetic anomalies are associated with these features and it is suggested that they are diapiric in origin. The eastern edge of the channel is much less pronounced the than western edge, with a gentle rise up onto the self.

Figure 3.3 Seismic section illustrating the junction of the Faeroes Block and the Norwegian Basin. The basement of the Faeroes Block is marked 'FB', the oceanic basement of the Norwegian Basin 'OB', the sea-bed 'S', and the location of the junction with an arrow & the letter 'J'. Note the discontinuity caused by a 1 second jump in the timing of the display (necessary to keep the top of the section within display range).

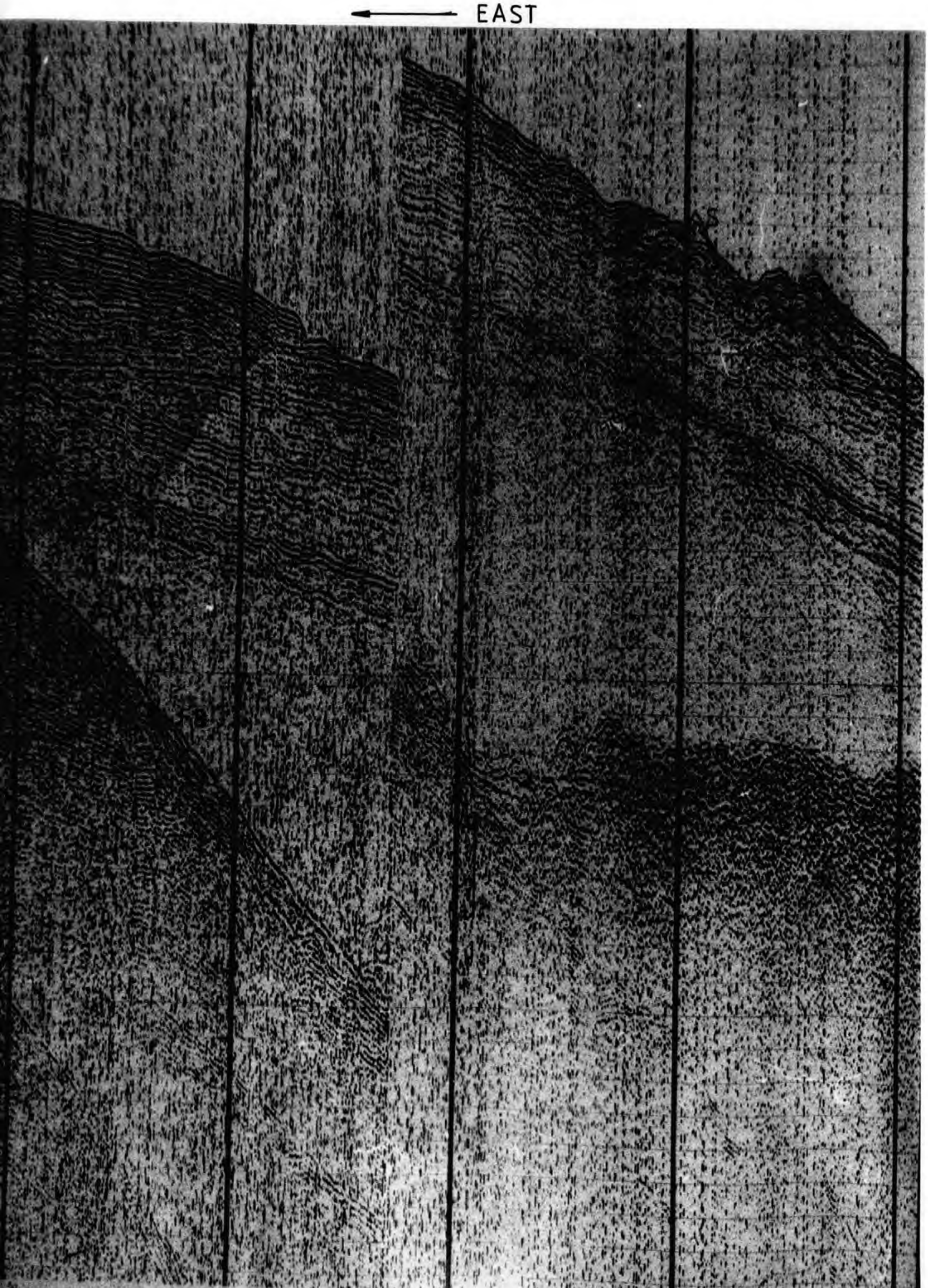
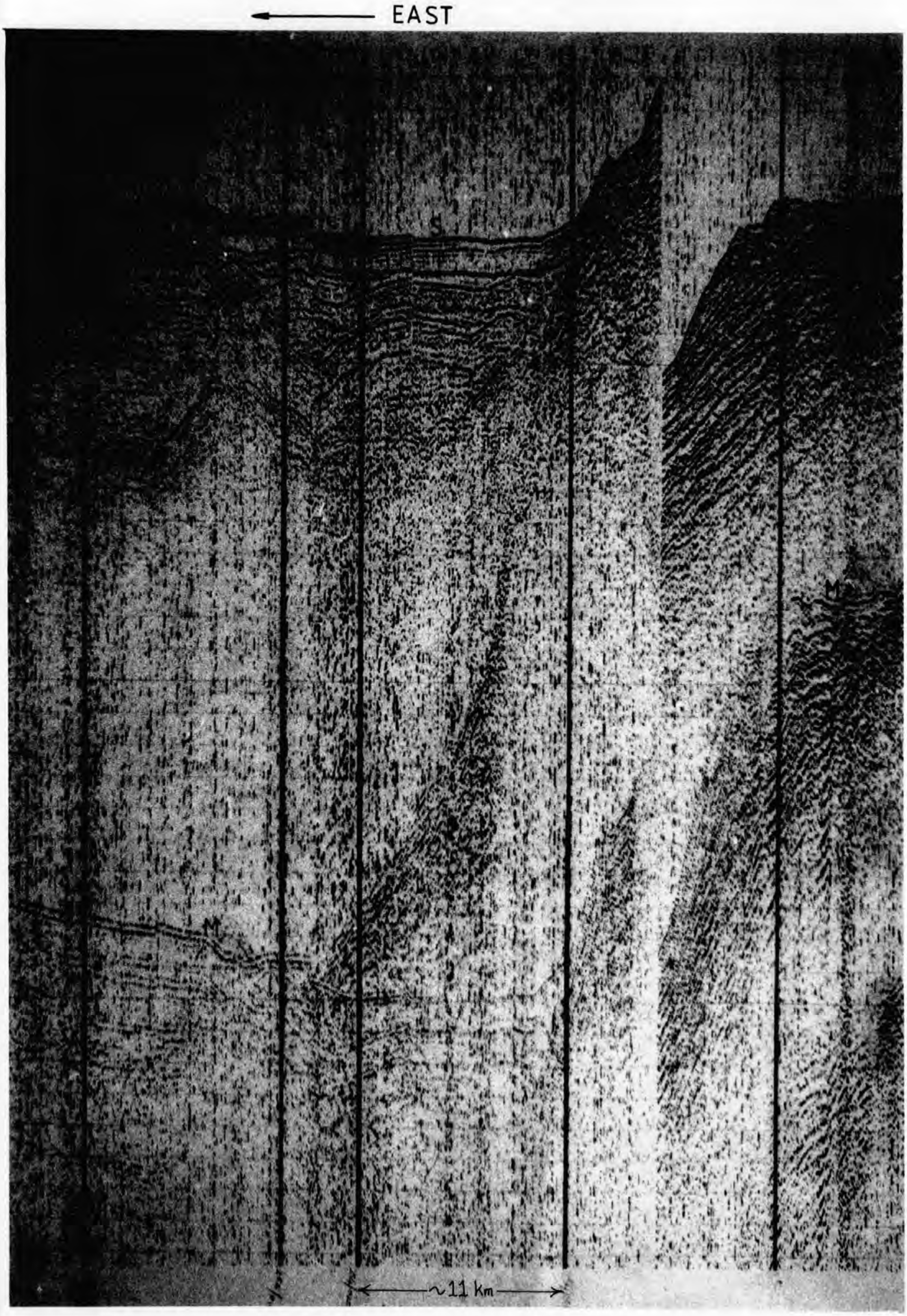

EAST
~ 11 Km

Figure 3.4 Seismic section across the eastern boundary of the Faeroes Block along line 4/76A. The Faeroes Block is to the right of the figure and the Faeroe-Shetland Channel to the left. Water bottom multiples (M) are visible on the section.


EAST
S
M
M
~11 km

The data from lines 4/76B and 9/77R which has been processed shows that there is a considerable difference between the acoustic basement beneath the Norwegian Basin and the acoustic basement over the structural high. Whereas the basement beneath the Norwegian Basin appears to be the oceanic layer 2, the reflector forming the top of structural high is smooth and is devoid of the roughness and diffraction hyperbolae which characterize oceanic basement. This smooth basement to the west of the Faeroe-Shetland Escarpment is shown in figure 3.5. On some of the unprocessed records it is possible to detect a change in the character of the basement reflector, which appears to take place at the seaward base of the structural high, although this is rather subjective.

A line drawing of the processed seismic section obtained along part of line 4/76B is given in figure 3.5. This section shows the prominent smooth reflector over the structural high to the west of the Faeroe-Shetland Escarpment and also shows that this reflector drops steeply eastwards to form the Faeroe-Shetland Escarpment, east of which the reflector gradually disappears beneath the sedimentary pile.

Figure 3.6 gives the position of all known seismic refraction profiles in the area. The data from these profiles is presented in Table 1. Most of the profiles were obtained using airguns as the seismic source and disposable sonobouys as the receivers, a system which gives reasonable definition of the shallow sedimentary structure. However, none of these sonobouy profiles succeeded in detecting the Moho. This was detected, using data from two-ship refraction profiles, at a depth of 7.2 km below sea-level beneath profile F-9 (figure 3.6) of Ewing and Ewing (1959) and at a depth of about 10 km below sea-level

Figure 3.5 Line drawing of the processed seismic section across the Faeroe Shetland Escarpment along line 4/76B.
The sea-bed is marked 'SB' and the Faeroe Shetland Escarpment is marked 'FSE'. The smoothness of the reflector to the northwest of the escarpment is evident when the vertical exaggeration is considered.

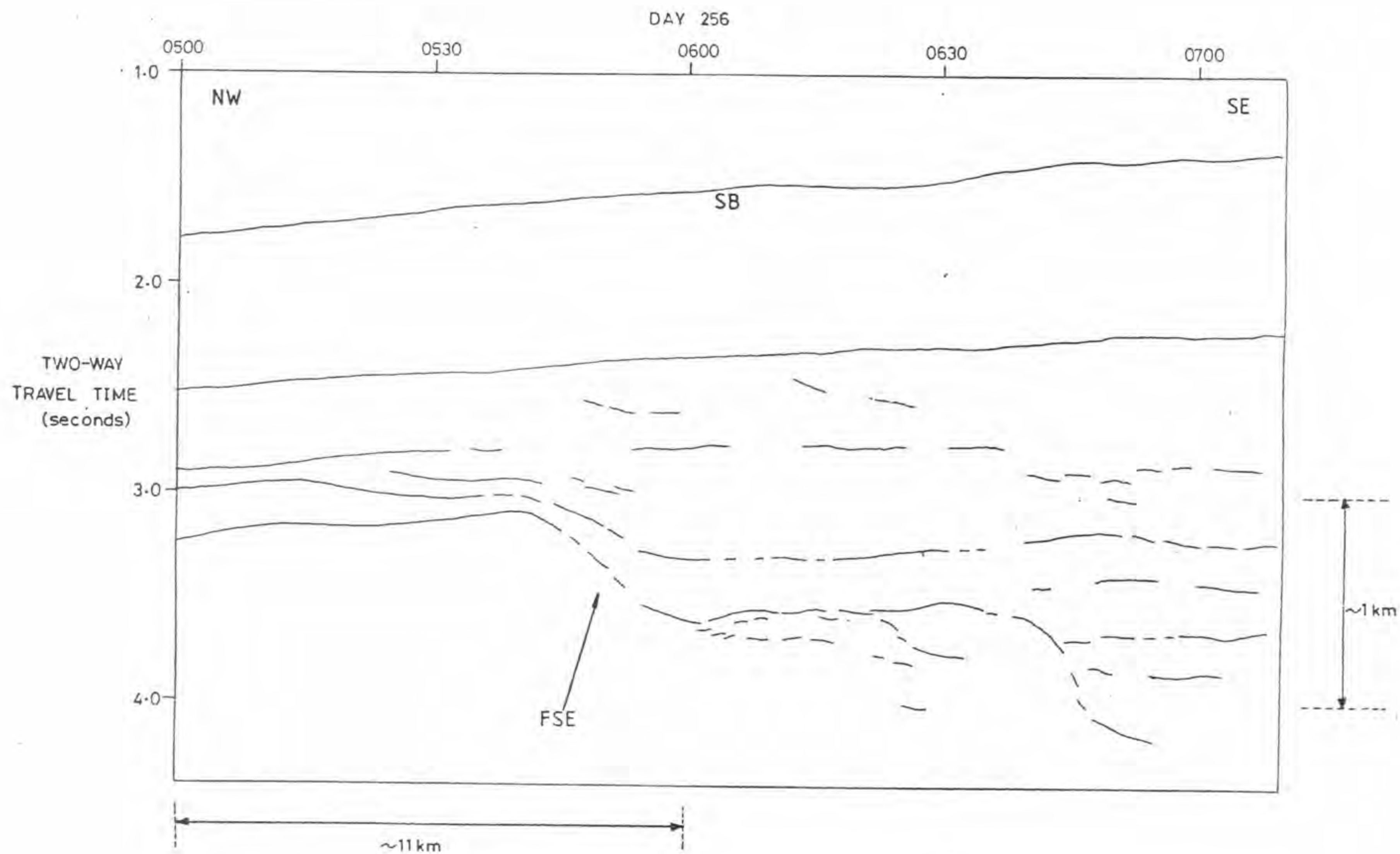
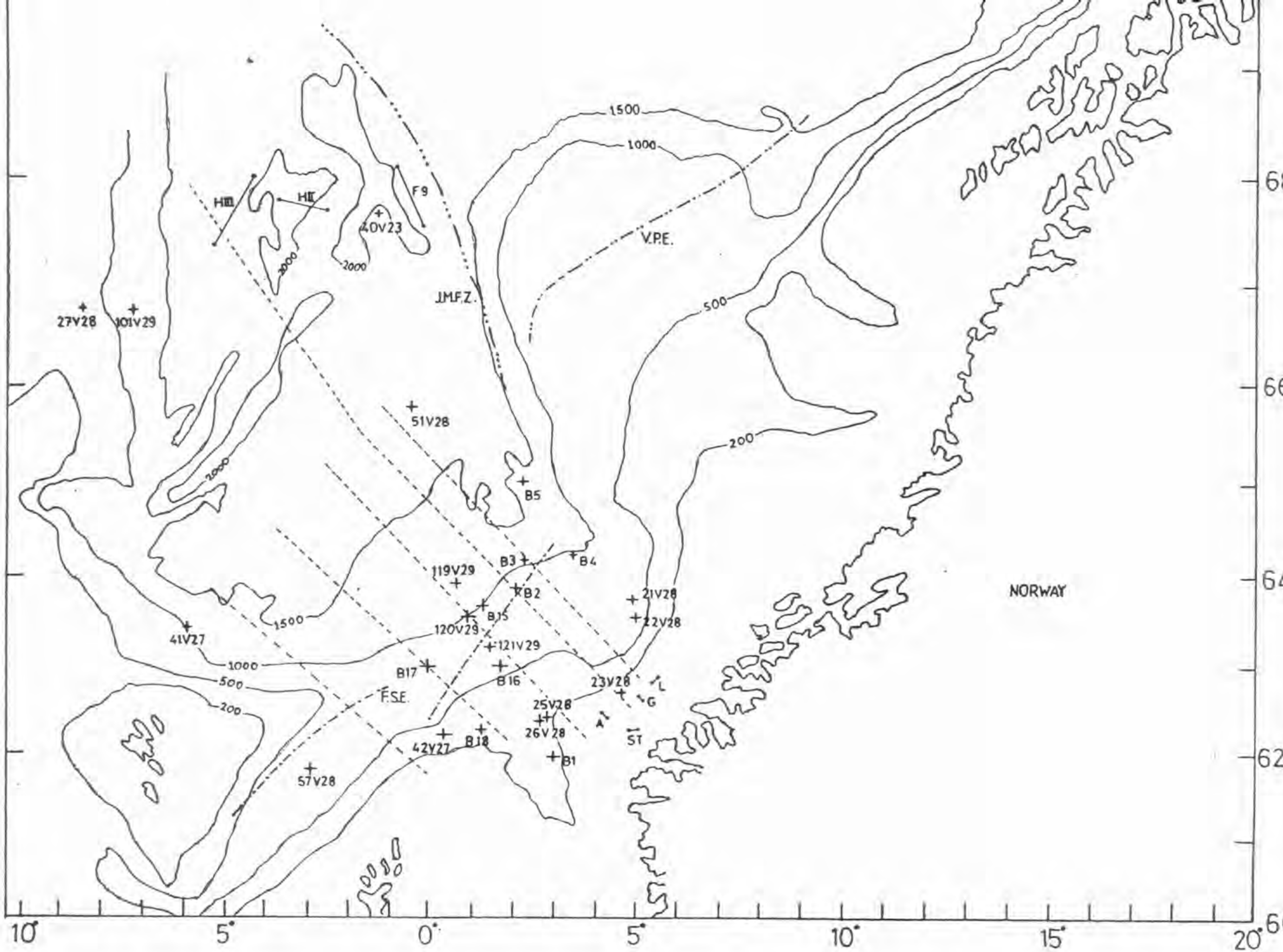

DAY 256
0500
0530
0600
0630
0700
1·0
2·0
3·0
4·0
TWO-WAY
TRAVEL TIME
(seconds)
NW
SE
SB
FSE
~11 km
~1 km

Figure 3.6 Location of all known seismic refraction profiles.

F.S.E. = Faeroe Shetland Escarpment

V.P.E. = Vøring Plateau Escarpment

J.M.F.Z.= Jan Mayen Fracture Zone.



27V28
101V29
HIII
HII
40V23
F9
2000
JMFZ.
V.P.E.
1500
1000
500
200
51V28
B5
B3
B4
119V29
B2
21V28
22V28
B15
120V29
121V29
41V27
B17
B16
23V28
F.S.E.
25V28
26V28
A
G
L
ST
42V27
B18
B1
57V28
NORWAY
10°
5°
0°
15°
20°
60°
62°
64°
66°
68°

Table 1 Listing of seismic refraction results.
All units in km and km/s.
Parentheses indicate assumed velocity.

Data Sources:-

B1 - B18	Sellevoll (1975)
40V23 - 57V28	Talwani and Eldholm (1972)
101V29 121V29	Gronlie and Talwani (1978)
* A,ST,G,L	Eldholm (1970)
* HII, HIII	Hinz and Moe (1971)
* F9	Ewing and Ewing (1959)

* reversed - all others unreversed.

Profile	Lat. (N)	Long. (-=W)	Water Depth	V1	H1	V2	H2	V3	H3	V4	H4	V5
B1	$61^{\circ}58'$	$2^{\circ}57'$	0.40	(1.80)	0.25	2.40	0.64	3.35	2.70	4.30	2.02	5.20
B2	$63^{\circ}51'$	$2^{\circ}00'$	1.66	1.76	0.59	2.10	1.00	5.00				
B3	$64^{\circ}09'$	$2^{\circ}09'$	1.50	2.00	0.56	5.05						
B4	$64^{\circ}14'$	$3^{\circ}22'$	1.85	1.82	0.80	2.20	0.76	3.50	2.57	5.20		
B5	$65^{\circ}00'$	$2^{\circ}08'$	2.50	2.15	1.08	5.10	1.00	6.45				
.B15	$63^{\circ}40'$	$1^{\circ}11'$	1.90	2.30	0.88	5.10						
B16	$63^{\circ}00'$	$1^{\circ}36'$	1.05	(1.80)	0.37	2.05	0.51	2.30				
B17	$63^{\circ}00'$	$-0^{\circ}10'$	1.44	2.25	2.06	5.30						
B18	$62^{\circ}16'$	$1^{\circ}07'$	0.50	(1.80)	0.32	2.10	1.68	2.55	1.02	3.95		
40V23	$67^{\circ}38'$	$-1^{\circ}23'$	3.59	1.92	0.88	2.85						
41V27	$63^{\circ}25'$	$-6^{\circ}00'$	1.65	1.67	0.64	2.26	1.27	4.55	1.16	6.40	0.80	6.70
42V27	$62^{\circ}13'$	$0^{\circ}16'$	0.67	(1.85)	0.43	2.02	1.51	3.32	0.70	4.65		
21V28	$63^{\circ}45'$	$4^{\circ}48'$	1.37	(1.85)	0.23	2.11	1.24	2.49	1.01	3.48		
22V28	$63^{\circ}33'$	$4^{\circ}56'$	1.19	(1.85)	0.49	2.09	1.15	2.44	0.71	3.43		
23V28	$62^{\circ}42'$	$4^{\circ}35'$	0.19	1.85	0.22	2.17	0.73	2.45	1.19	3.10	0.92	3.85
25V28	$62^{\circ}26'$	$2^{\circ}45'$	0.40	(1.85)	0.47	1.94	0.43	2.28	0.51	2.85		
26V28	$62^{\circ}23'$	$2^{\circ}35'$	0.40	(1.85)	0.34	1.97	0.32	2.38	0.58	2.88		
27V28	$66^{\circ}47'$	$-8^{\circ}30'$	1.72	1.96	1.03	3.52						
51V28	$65^{\circ}46'$	$-0^{\circ}37'$	3.15	2.20	0.77							
57V28	$61^{\circ}47'$	$-2^{\circ}59'$	1.52	1.63	0.40	2.19	1.04	2.62	0.89	3.19		
101V29	$66^{\circ}44'$	$-7^{\circ}18'$	2.10	1.71	0.34	2.05	0.93	2.50	1.31	5.88		
119V29	$63^{\circ}55'$	$0^{\circ}34'$	2.31	1.62	0.30	2.02	0.71	4.49				
120V29	$63^{\circ}31'$	$0^{\circ}49'$	1.90	1.58	0.76	2.06						
121V29	$63^{\circ}13'$	$1^{\circ}23'$	1.25	1.87	1.24	2.12	0.83	2.68				
A	$62^{\circ}27'$	$4^{\circ}20'$	0.17	1.82	0.38	2.28	1.10	2.79	0.75	3.33	1.70	5.00
	$62^{\circ}31'$	$4^{\circ}10'$			0.59		1.10		0.75		1.70	
ST	$62^{\circ}16'$	$4^{\circ}58'$	0.18	2.01	0.00	2.51	0.00	5.60				
	$62^{\circ}17'$	$4^{\circ}48'$			0.23		0.22					
G	$62^{\circ}35'$	$5^{\circ}06'$	0.10	1.95	0.30	2.17	0.56	2.62	0.92	3.57	1.61	5.25
	$62^{\circ}40'$	$4^{\circ}59'$			0.56		0.59		0.64		1.57	
L	$62^{\circ}52'$	$5^{\circ}29'$	0.10	1.94	0.46	2.09	0.52	2.45	0.78	3.60		
	$62^{\circ}49'$	$5^{\circ}20'$			0.46		0.54		1.05			
HII	$67^{\circ}42'$	$-2^{\circ}36'$	3.80	2.10	0.90	4.50	1.00	7.50	4.30	8.30		
	$67^{\circ}49'$	$-3^{\circ}48'$										
HIII	$68^{\circ}04'$	$-4^{\circ}49'$	3.65	2.50	0.80	3.85	2.00	6.60	3.55	8.20		
	$67^{\circ}32'$	$-5^{\circ}17'$										
F9	$67^{\circ}31'$	$-0^{\circ}14'$	3.36	1.70	0.12	1.87	0.77	5.35	2.82	8.04		
	$68^{\circ}06'$	$-0^{\circ}54'$										

along profile III of Hinz and Moe (1971). The oceanic crust is anomalously thin in the region of profile F-9 if the refraction results are correct, but as the profile was located close to the Jan Mayen Fracture Zone an atypical result is not unexpected. This contrasts with the profile of Hinz and Moe, which was shot in a region of linear oceanic magnetic anomalies, and which yielded a crustal structure typical of ocean basins.

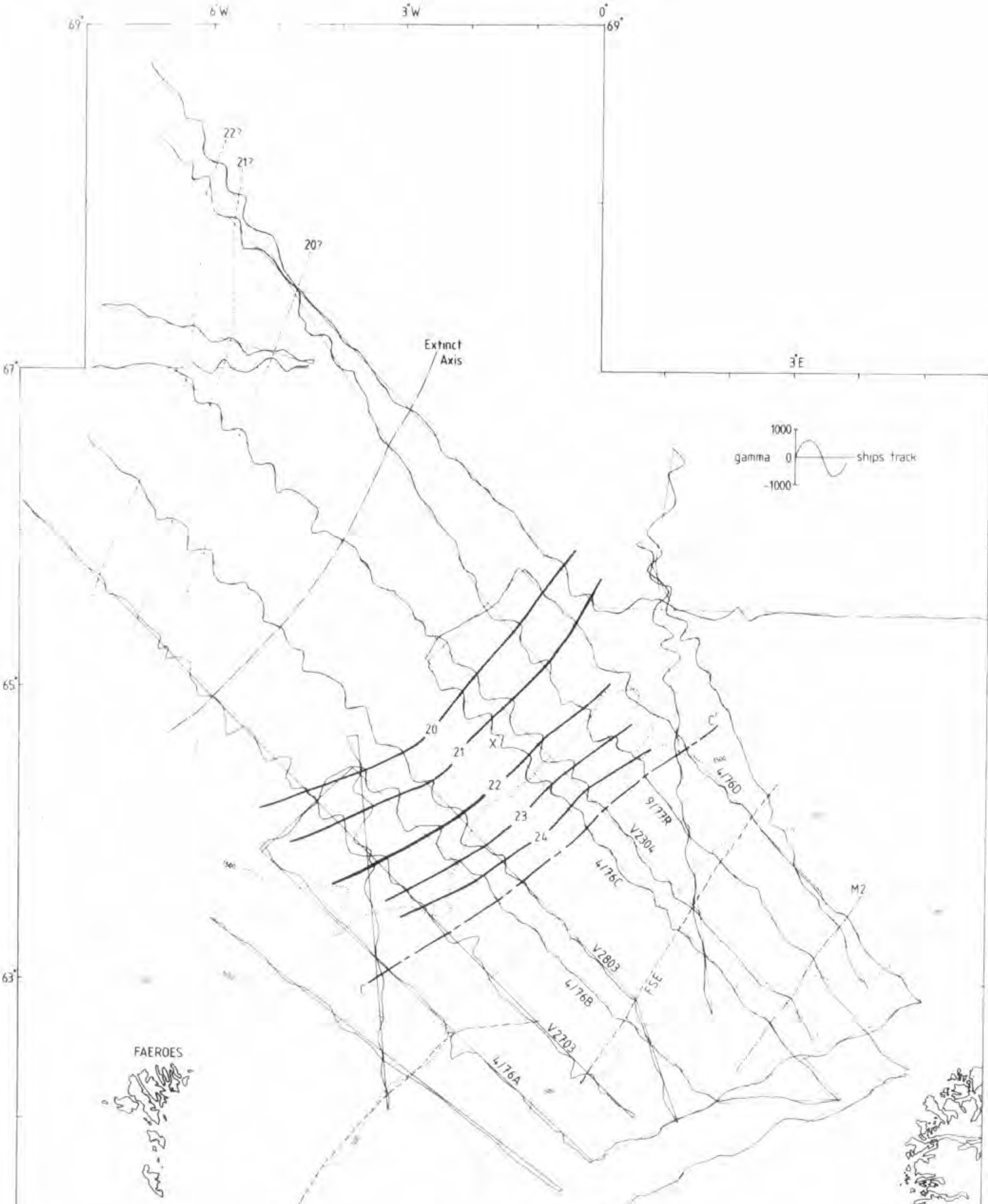
The prominent reflecting horizon detected over the structural high corresponds to the top of the layer with a velocity of around 5.00 km/s that is found on the refraction profiles obtained from west of the Faeroe-Shetland Escarpment. The high velocity of this layer in comparison to the velocities of the overlying sedimentary layers accounts for its high reflectivity. This layer is visible on profiles B2, B3, B5, B15 and B17 (Sellevoll, 1975) but not on profile 120V29 (Gronlie and Talwani, 1978) which did not penetrate deep enough and not on profile 119V29 (Gronlie and Talwani, 1978) which was shot further northwest. No refractors are seen below the 5.00 km/s layer except on profile B5 where a layer with a velocity of 6.45 km/s was detected at a depth of 4.5 km.

The 5.00 km/s layer has not been detected on any of the refraction profiles shot to the east of the Faeroe-Shetland Escarpment. In this area the refraction profiles reveal a gradual increase of velocity with depth and indicate that there is a great thickness of sediments within the basin. It has been found in the North Sea that Tertiary sediments rarely have seismic velocities in excess of 2.25 km/s (Hornabrook, 1967; Wyrobek, 1969) so it is suggested that the layers detected within the basin with velocities greater than 2.5 km/s represent Mesozoic sediments. The deeper layers have velocities greater than 4.0 km/s which, according to Talwani and Eldholm (1972) may represent late Palaeozoic sediments. The deepest refractor found in the basin has a velocity of about 5.2 km/s and was detected at a depth of approximately 6 km. This velocity is rather low for continental basement which is generally considered to have a velocity of approximately 5.9 - 6.2 km/s, so this layer could represent highly compacted sedimentary material or oceanic layer 2. The latter case could arise if there is a northern extension of the Faeroe-Shetland Channel, assuming that the channel was formed by sea-floor spreading. This possibility is discussed later.

3.3 Magnetic data.

The magnetic anomalies observed during the 1976 and 1977 cruises are plotted along simplified ship's track in figure 3.7, together with data obtained by the Lamont-Doherty Geological Observatory. It is clear that the magnetic anomalies divide the area into two distinct zones. To the northwest in the deep water Norwegian Basin there are the characteristic long wavelength linear magnetic anomalies generated by sea-floor spreading (Vine and Matthews, 1963) which give way southeastwards to an extensive marginal quiet zone similar to those found along many of the world's rifted continental margins (Heirtzler and Hayes, 1967; Vogt et. al., 1970a). The quiet zone extends eastwards over the continental slope and shelf as far as the Norwegian coast with low amplitude anomalies typically less than 200 gamma. Some of the larger anomalies within the quiet zone may be correlated between profiles and give the lineations M1 and M2 shown in figures 3.7 and 3.9 (lineation M1 is denoted as the northern section of the Faeroe-Shetland Escarpment in figure 3.7). The general level of the anomalies within the quiet zone is negative, the only extensive region of positive anomalies occurring in the south (figure 3.7).

Figure 3.7 Magnetic anomalies in the Norwegian Basin plotted along simplified ship's track for all Durham and some Lamont Doherty profiles. C-C' = proposed Continent - Ocean Boundary.



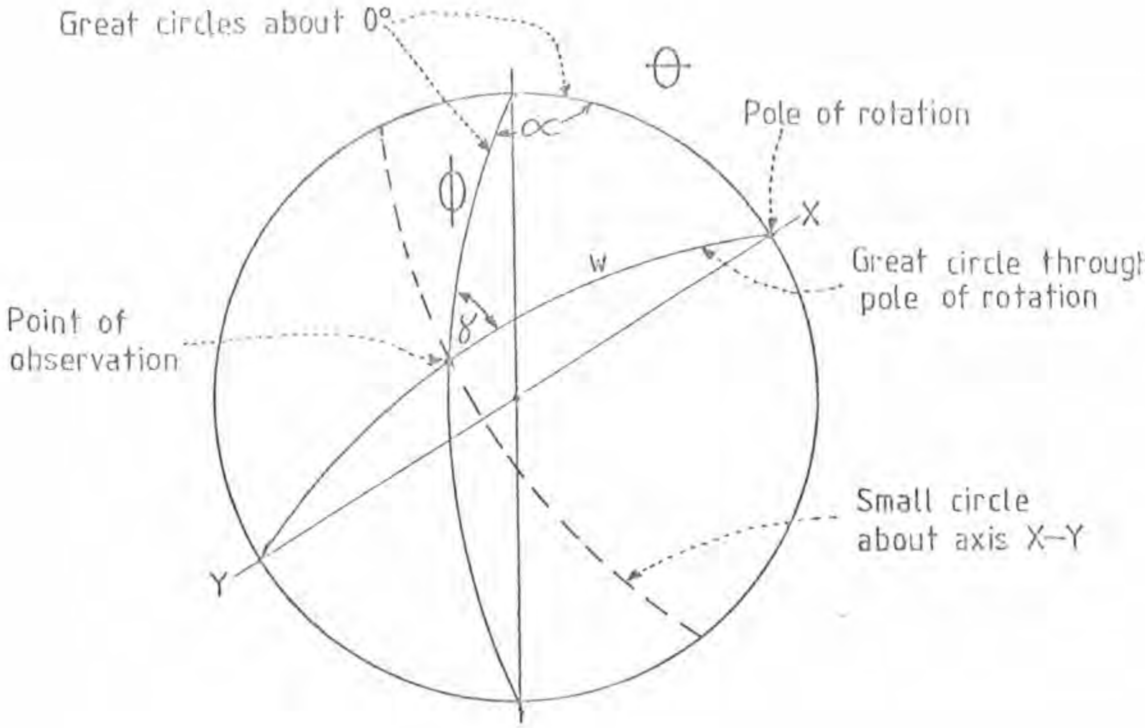
6°W
3°W
0°
69°
3°E
67°
65°
63°
61°
9°W
6°E
22?
21?
20?
Extinct Axis
1000
gamma
0
-1000
ships track
20
21
22
23
24
X
C
C'
4/76D
9/77R
V2304
4/76C
V2803
4/76B
V2703
4/76A
FSE
M2
FAEROES

3.3.1 Oceanic magnetic anomalies and their identification.

In the Norwegian Basin it is not possible to identify and number the linear oceanic anomalies by "counting-back" from the present axial anomaly, as is possible in the Lofoten Basin to the north and in the Atlantic Ocean to the south, because the observed anomalies were not formed along the present spreading axis. Instead they were created along an extinct spreading ridge located near to the centre of the basin (Vogt et. al., 1970b). Thus the identification of the anomalies has been achieved via computer modelling using published spreading-rate data.

As all relative plate motions on a spherical earth can be considered as rotations about an axis passing through the centre of the earth, in accordance with Euler's "fixed-point theorem", analysis of the azimuths of fracture zones will yield the position of the pole of rotation for the plates concerned. Such an analysis was carried out by Talwani and Eldholm (1977) who calculated that the pole of total opening between Greenland and Europe lies at 41.7°N, 124.5°E, and that the finite difference pole between the time of the initial opening and anomaly 21 time (ie the pole of rotation about which Greenland and Europe rotated between the time of the initial opening and anomaly 21 time) occurs at 5.74°S, 124.9°E. Given the pole of opening one is able to calculate the direction of spreading at any point on the earth, as illustrated in figure 3.8. For the two poles given above this method results in spreading azimuths of 129° and 150° respectively for the opening of the Norwegian Basin. For the purposes of matching calculated and observed magnetic anomalies, the finite difference pole is applicable, as this gives the actual spreading azimuth during the opening between anomaly 24 time and

Figure 3.8 The calculation of the azimuth of spreading between two plates.



ϕ = colatitude of point of observation

θ = colatitude of pole of rotation

α = difference in longitudes

$90+\gamma$ = azimuth of spreading

By spherical triangles :- $\cos w = \cos\phi . \cos\theta + \sin\phi . \sin\theta . \cos\alpha$

and $$\frac{\sin w}{\sin\alpha} = \frac{\sin\theta}{\sin\gamma}$$

thus $$\gamma = \sin^{-1}\left(\frac{\sin\theta . \sin\alpha}{\sin w}\right)$$

and azimuth of spreading $= 90 + \sin^{-1}\left(\frac{\sin\theta . \sin\alpha}{\sin w}\right)$

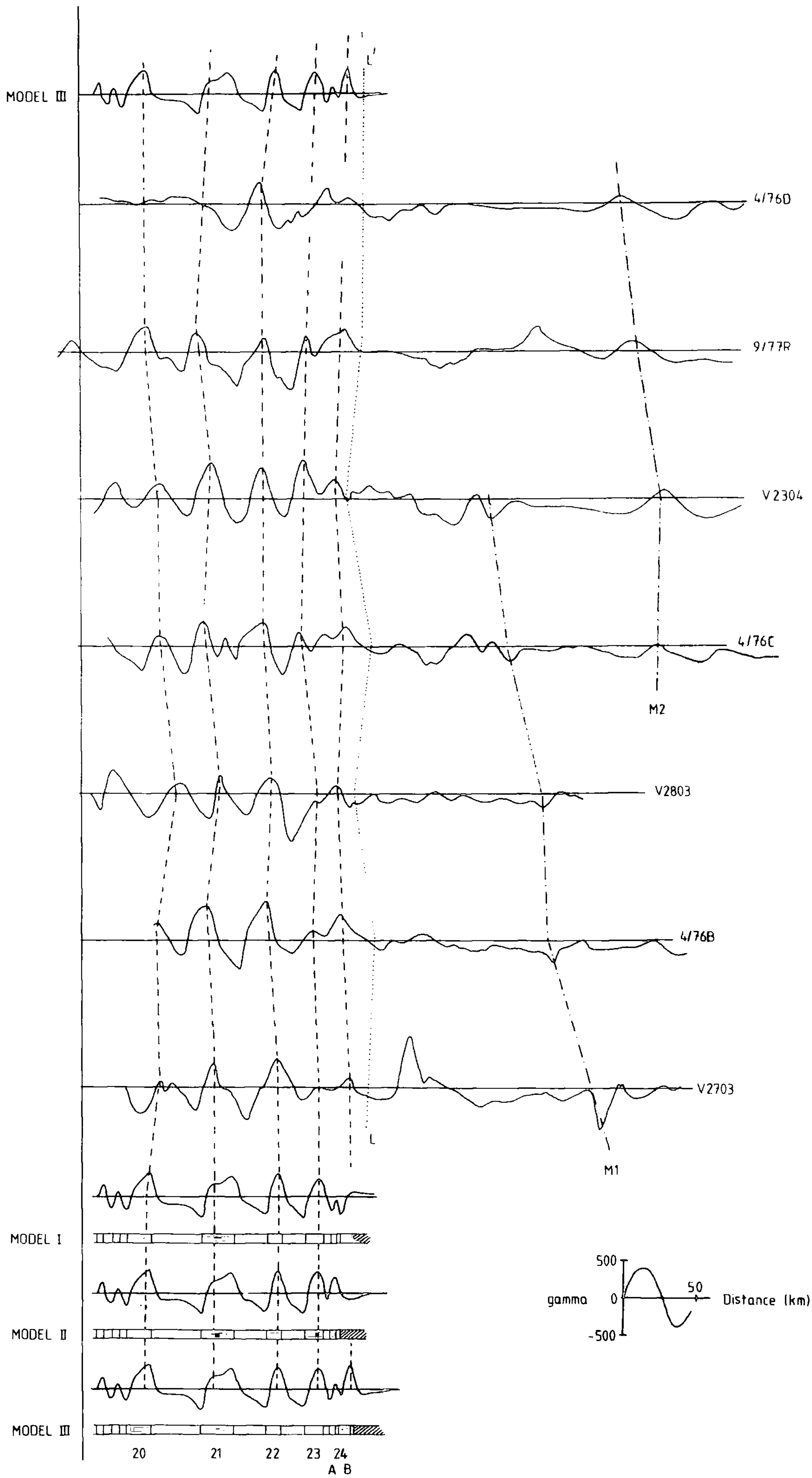
anomaly 21 time, and consequently a spreading azimuth of 150° has been used in all subsequent work.

A theoretical magnetic anomaly pattern in the direction of spreading has been calculated using the spreading rates deduced for the Mohns Ridge (Talwani and Eldholm, 1977), which show that northern Greenland and northern Norway separated at the rate of 1.52 cm/yr between anomaly 18 time and anomaly 20 time, and at the rate of 2.50 cm/yr between anomaly 20 time and the time of the initial opening. In constructing the synthetic anomaly pattern it was assumed that the magnetic inclination and declination in the early Tertiary were the same as they are today. The theoretical anomaly pattern and the model used to generate it are shown in figure 3.9 together with seven observed profiles across the margin, each projected onto an azimuth of 150°. The broad overall agreement between the theoretical pattern and the observed profiles shows that the assumptions used in the construction of the model are basically sound.

It is clear from figure 3.9 that Talwani and Eldholm (1977) were correct in their tentative indentifaction of anomalies 20, 21 and 22, at least in the eastern part of the basin. Moreover anomaly 23 can clearly be identified on all of the profiles except 4/76D, and is marked as such in figure 3.9.

It is believed that the positive anomaly to the east of anomaly 23 is anomaly 24, although there is some doubt about this. The Heirtzler time scale used in this thesis, in common with more modern timescales (eg. LaBrecque et. al., 1977), shows anomaly 24 consisting of two periods of normal polarity separated by an interval of reversed polarity. This is illustrated by Model 1 in figure 3.9, with the older of the two positively magnetized stripes abutting onto

Figure 3.9 Observed and Theoretical magnetic anomaly pattens in the eastern Norwegian Basin.
L-L' = magnetic low.
All lines have been projected onto 150°.



MODEL III
L'
4/76D
9/77R
V2304
4/76C
M2
V2803
4/76B
V2703
L
M1
MODEL I
MODEL II
MODEL III
20
21
22
23
24
A B
500
gamma
0
-500
50
Distance (km)

non-magnetic continental material. This type of model gives rise to two separate positive anomalies for anomaly 24, whereas only one peak is seen on the observed profiles, although a wide, possibly double, peak is seen along line 9/77R. The positive peak about 15 km east of anomaly 23 on line 4/76C is probably due to an intrusive body visible on the seismic records. A further problem is that landward of the eastern-most oceanic anomaly a magnetic low is seen on all of the profiles (marked L-L' in figure 3.9). If the initial rift and spreading occurred during a period of normal polarity, as in Model 1 of figure 3.9, then one should see a magnetic high to the east rather than a low. A reasonable synthetic pattern can only be generated if the oceanic crust abutting onto the continental mass is reversely polarized. Therefore it can be postulated that sea-floor spreading within the Norwegian Basin began during a period of reversed magnetic polarity, and thus there are three possible periods when spreading could have started;- (a) between anomaly 23 and anomaly 24A, (b) between anomalies 24A and 24B, and (c) between anomaly 24B and anomaly 25 time.

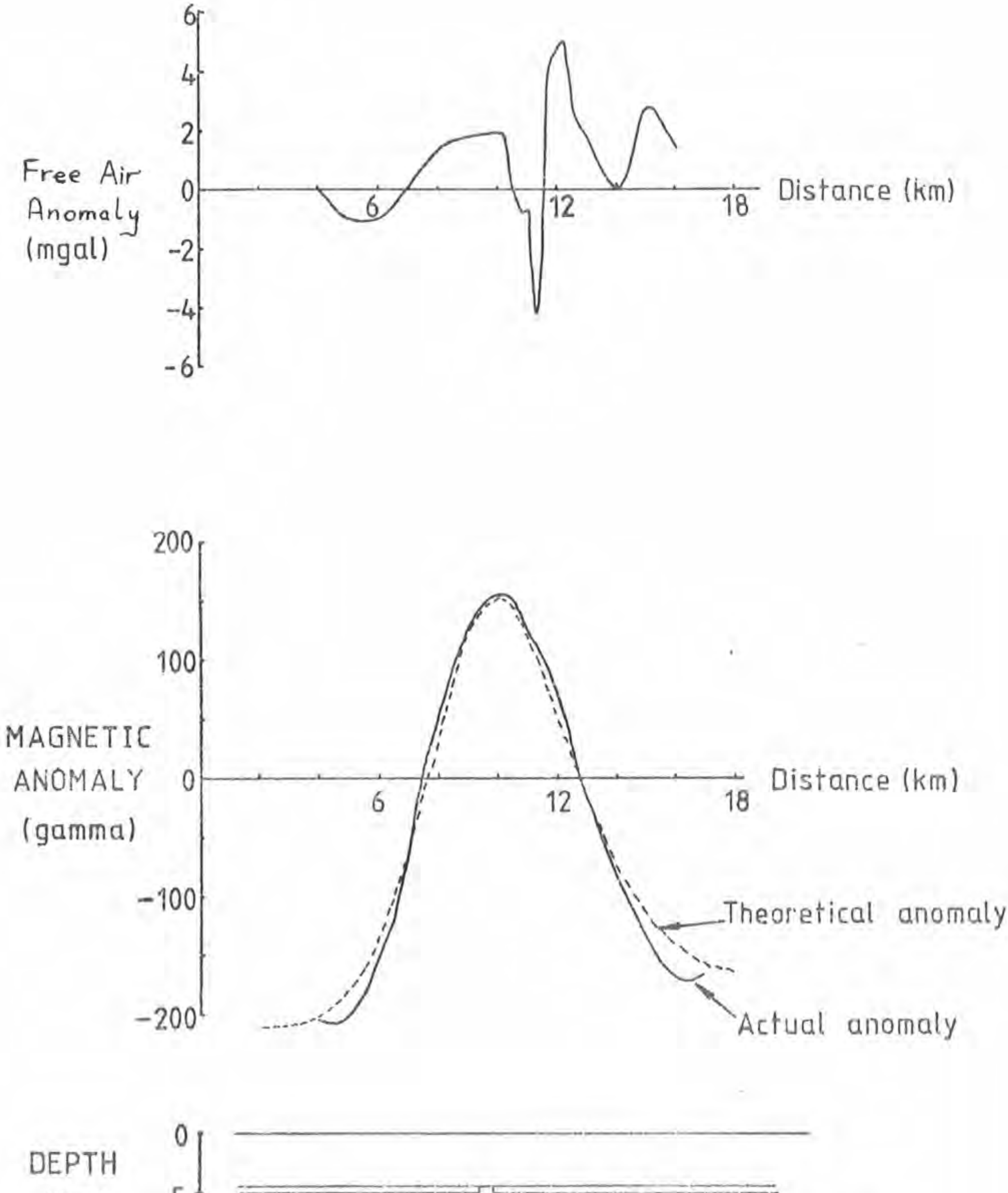
It is difficult to see how the positive peak to the east of anomaly 23 could have been created if the spreading had commenced between anomaly 23 and anomaly 24A time, so this possibility is discounted. Models representing the outcome of the other two possibilities are shown in figure 3.9 as Models II and III respectively, together with their synthetic anomaly patterns. Model II generates only one positive peak for anomaly 24 but puts it much closer to anomaly 23 than the anomaly observed on the actual profiles. However the distance calculations are based on data from outside the Norwegian Basin and may not be accurate for the area. Also it is possible that when the final split between the plates occurs the initial spreading rate is quite high, which could give the extra distance seen on the observed profiles. This type of behaviour is not accounted for in the models, which have been constructed on the assumption that the plates move apart at 2.50 cm/yr from the instant that the split occurs. The alternative explanation (Model III) puts anomaly 24B in approximately the correct place with respect to anomaly 23 but also gives a small positive peak corresponding to anomaly 24A. Both models generate the requisite magnetic low to the east. It is difficult to decide between these two possibilities, but in view of the good agreement between the observed distance between anomalies 23 and 24 and the calculated offset of anomaly 24B from anomaly 23, it is believed that Model III represents the most likely possibility. Thus it is suggested that sea-floor spreading between Greenland and Norway began between anomaly 24B time and anomaly 25 time. A similar conclusion was reached by Eldholm (1978) from a study of the Norwegian margin to the north of 65°N.

The identified anomalies have been marked on figure 3.7 and it is noticeable that the linear oceanic anomalies exhibit a change in trend from W.S.W. - E.N.E. to S.W. - N.E. between lines V2803 and 4/76C, together with a small offset of approximately 15 km. The aeromagnetic map of the area (Avery et. al., 1968) also shows a dislocation of the anomalies in the same region, but this data is not very reliable as it was gathered on widely spaced flightlines which have considerable position-fixing uncertainties. It is possible that the dislocation is caused by a small N.W. - S.E. trending fracture zone though there is no indication of such a feature on the gravity map of Gronlie and Talwani (1978) or on any seismic profiles.

Along line 4/76C the magnetic low generated by the reversely magnetized crust formed between anomaly 21 time and anomaly 22 time is disturbed by the presence of a positive anomaly, marked as "X" in figure 3.7. This positive anomaly in no way fits the theoretical anomaly profile, nor can it be traced laterally onto profiles V2803 or V2304, and it is thus attributed to a local structure. The seismic records show a slight doming of the basement coincident with the anomaly. It is therefore suggested that the anomaly is due to an igneous intrusion introduced into the crust during a period of normal magnetic polarity some time after anomaly 21 time. Estimates of the depth to the intrusion using the dyke-based method of Am (1972) gave depths that are much too shallow, in all cases being shallower than the sea-bed. This error is due to the assumption in the dyke-based method that the anomaly-causing body is two-dimensional, an assumption that is invalid in this case. Spectral analysis methods (T.L. Armstrong, pers. comm.) yield a depth to the body of approximately 6.5 km which may be slightly deep. Computer modelling indicates that the anomaly-causing body must be very highly magnetized, as it is not possible to generate very steep magnetic anomaly gradients from a deep source without a high magnetization contrast between the body and its surrounds. A reasonable fit between observed and calculated anomalies may be achieved using a simple intrusion model, as shown in figure 3.10. The intrusion is of the order of 0.5 km in width and has a magnetization of approximately 40 A/m, and is therefore more likely to be a small volcanic centre than a dyke. The gravity field shows a slight disturbance over the feature, as illustrated in figure 3.10. The gravity values shown have been taken directly from the raw chart-recorder records as the reduced data profiles have too coarse a sampling rate to accurately define the anomaly.

The areal extent of the linear oceanic anomalies can be seen in figure 3.7. In the southwest of the basin the anomalies die out between lines V2703 and 4/76B. This termination is also seen on the

Figure 3.10 Magnetic model of an intrusion along line 4/76C.



Free Air Anomaly (mgal)
6
4
2
0
-2
-4
-6
6
12
18
Distance (km)
MAGNETIC ANOMALY (gamma)
200
100
0
-100
-200
6
12
18
Distance (km)
Theoretical anomaly
Actual anomaly
DEPTH (km)
0
5
Magnetization = 40 A/m

aeromagnetic map of Avery et. al., (1968). It seems likely that this disappearance of the linear anomalies is related to the presence of the Iceland-Faeroe Ridge, which forms the southwestern boundary of the basin. It may be that the termination of the anomalies marks the boundary between oceanic crust formed below sea-level and that, as on the Iceland-Faeroe Ridge, formed above sea-level, although if this were the case then one might expect to see a different structure and texture in the seismic records of line 4/76A when compared to those from the area to the northeast, a difference that is not seen. It should also be noted that the Iceland-Faeroe Ridge has high amplitude, short wavelength magnetic anomalies associated with it, but that the region between the ridge and the linear anomalies has a quiet magnetic signature similar to the marginal quiet zone. The presence of the Faeroes lava flows is another complication within this region as it is not known how far they extend.

The Jan Mayen Fracture Zone is responsible for the northern truncation of the anomalies, offsetting them from the anomalies formed along the Mohns Ridge. The linear oceanic anomalies die out between line 9/77R and line 4/76D, being replaced by a disturbed magnetic regime with short wavelength, high amplitude anomalies which do not show any recognisable orientation and which probably represent fractured oceanic crust. At its southeastern end the fracture zone may be formed by a series of blocks rather than by a single linear transform fault (Sellevoll, 1975).

3.3.2 The magnetic quiet zone and anomalies within it.

The sea-floor spreading anomalies found within the Norwegian Basin are succeeded landwards by an extensive magnetic quiet zone that stretches southeast across the continental slope and shelf as far as the

Norwegian coast. Small, irregular anomalies do occur within the zone, but with the exception of those anomalies forming lineations M1 and M2 (figure 3.9) they cannot be correlated laterally between profiles. The magnetic field is at its quietest around 63^{o}N, 0^{o}W becoming more disturbed to the northeast and to the south into the North Sea. The overall level of the anomalies is negative, the only extensive region of positive anomalies occurring in the south. Whilst the magnetic anomalies within the zone are generally of low amplitude, and the overall magnetic field is much less disturbed than in the oceanic region, the magnetic field in the area is still much more disturbed than the magnetic quiet zone over the Inner Vøring Plateau where the field is exceptionally smooth (Avery et. al., 1968; Am, 1970).

Two lineations cross the quiet zone, marked as M1 and M2 in figure 3.9. These lineations were first reported by Avery et. al. (1968) who interpreted them as indicating the northeastern extensions of the Minch and Great Glen Faults respectively. An alternative explanation was proposed by Talwani and Eldholm (1972), who noted that the lineation M1 is coincident with the Faeroe-Shetland Escarpment and, in their opinion, marks the seaward limit of the magnetic quiet zone, so that all of the anomalies to the northwest are of oceanic origin. Thus they associated the lineation with the site of the initial rifting in the region. They also showed that lineation M2 does not extend south of latitude 62^{o}N, and that it has a more westerly trend than the line given by Avery et. al. (1968), and therefore it could not be considered as representing a continuation of the Great Glen Fault.

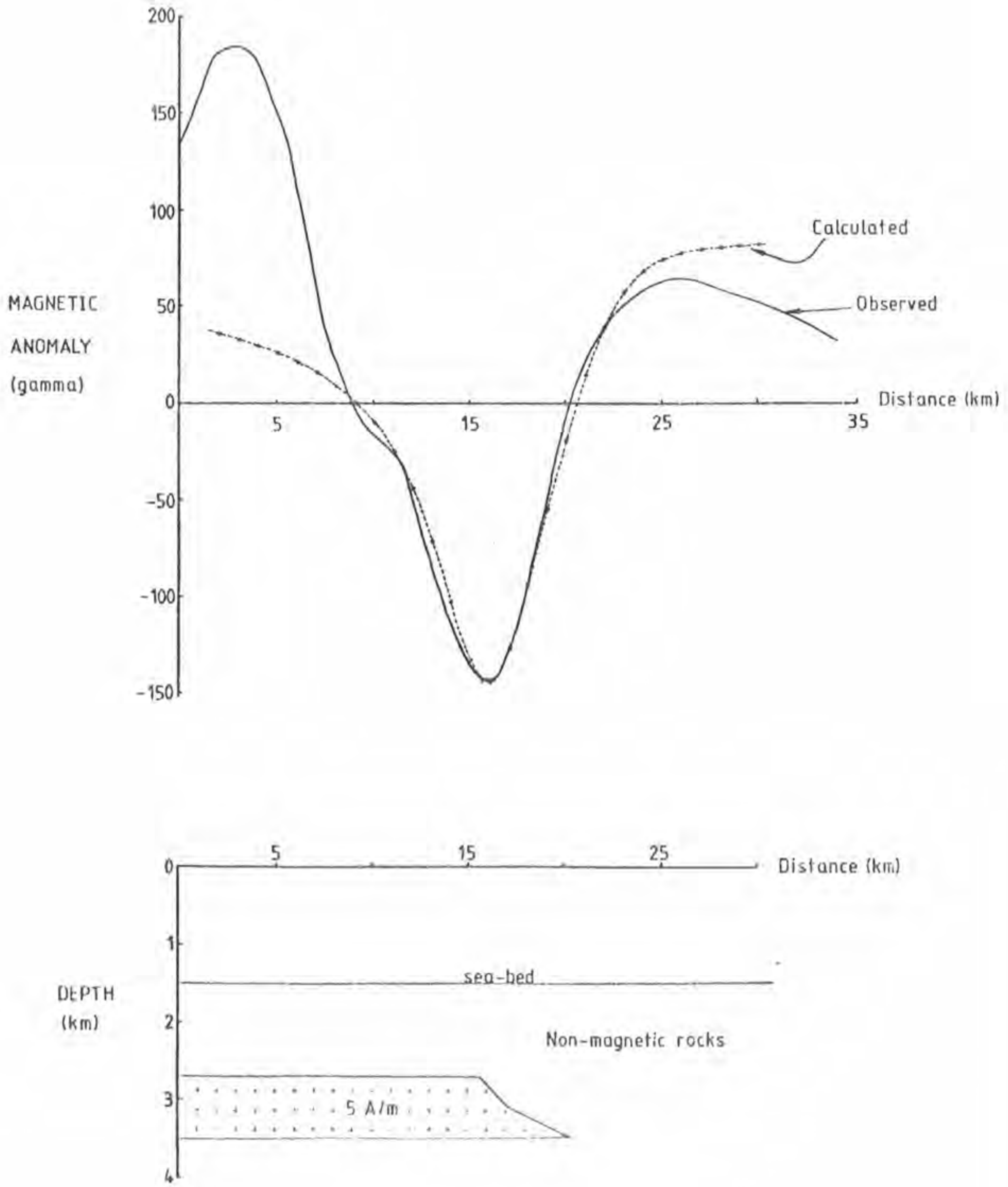
Estimates of the depth to the sources of lineations M1 and M2 have been made using the dyke-based parameter method of Am (1972) and a spectral analysis method (T.L. Armstrong, pers. comm.). Along line 4/76B the parameter method yielded a depth of 2.50 km to the top of the source of M1 while the spectral analysis method gave a depth of 2.73 km. The seismic reflection records show that the Faeroe-Shetland Escarpment lies between 2.6 km and 3.1 km below sea-level (assuming a velocity of 2.00 km/s for the overlying sediments). Similarly, along line 4/76C the seismic records show the escarpment between 2.5 km and 3.5 km below sea-level, while the parameter method gives a depth of 2.35 km and the spectral method gives a depth of 3.84 km. It is therefore concluded that the Faeroe-Shetland Escarpment must be the cause of the lineation. This magnetic anomaly has been modelled using a simple "thinning slab" model, as illustrated in figure 3.11, and a reasonable fit to the observed anomaly has been obtained. The model shows that the material over the structural high, whose termination forms the Faeroe-Shetland Escarpment, is reversely magnetized and has a magnetization of about 5 A/m, assuming that it has a thickness of 800 m. This implies that the material is igneous in origin, as such a magnetization is greater than the magnetization normally attributed to metamorphic basement.

The lineation M2 is crossed by three Durham traverses, 4/76C, 9/77R and 4/76D, and depth estimates were obtained from each of these lines using the same methods. The parameter method gave depths of 13.86 km, 10.25 km and 8.24 km respectively while the spectral method yielded depths of 12.30 km, 13.56 km and 12.90 km respectively. Depths of the order imply that the source of the lineation lies within the basement beneath the sedimentary pile.

3.4 Gravity data.

The free air gravity anomalies observed during the Durham cruises and several of the Lamont-Doherty cruises are shown along simplified

Figure 3.11 Magnetic model of the Faeroe-Shetland Escarpment.



200
150
100
50
0
-50
-100
-150
MAGNETIC
ANOMALY
(gamma)
Calculated
Observed
Distance (km)
5
15
25
35
0
1
2
3
4
DEPTH
(km)
sea-bed
Non-magnetic rocks
5 A/m

ship's track in figure 3.12. The gravity field is seen to be fairly subdued, with no steep gradients and no large peaks or troughs, which is in agreement with the gravity map of Gronlie and Talwani (1978). A gravity high is present over the Norwegian Basin but it decreases landward over the margin before increasing again over the shelf.

The free air gravity anomaly along each Durham traverse is plotted in profile form in figures 3.13(a)-(e), together with the magnetic anomalies observed along the profiles. Computer modelling of the gravity anomalies has been undertaken for each of the profiles and the resultant crustal models and synthetic free air anomalies are also shown in figures 3.13(a)-(e). The broad trends of the theoretical and observed anomalies match reasonably well, but no attempt has been made to match the short wavelength anomalies as it is considered that the lack of knowledge concerning the detailed structure of the region would render meaningless any such attempt. In constructing the models it has been assumed that the upper mantle has a uniform density of 3.30 g/cm^3 and that both the oceanic and continental crusts have uniform densities of 2.85 g/cm^3. The lower sediments within the deep sedimentary basin on the shelf are assumed to have a density of 2.45 g/cm^3. The water is assumed to have a density of 1.03 g/cm^3, while the unconsolidated and semi-consolidated sediments have been allotted a density of 2.00 g/cm^3. The bathymetry was obtained directly from the cruise data tapes and has been corrected for variations in water temperature, salinity and pressure by the Matthews corrections for the area (Matthews, 1939). The base of the unconsolidated and semi-consolidated sediments has been found from the seismic reflection records, the two-way travel time being converted into depths by assuming that the sediments have an average seismic velocity of 2.00 km/s. The depth to the base of these sediments is

Figure 3.12 Free Air gravity anomalies within the Norwegian Basin plotted along ship's track for all Durham and some Lamont Doherty profiles.

C-C' = Proposed Continent - Ocean Boundary

T1 = Line of maximum crustal thickness

T2 = Line of minimum crustal thickness.

S1-S2 = Position of seismic section shown in figure 4.5

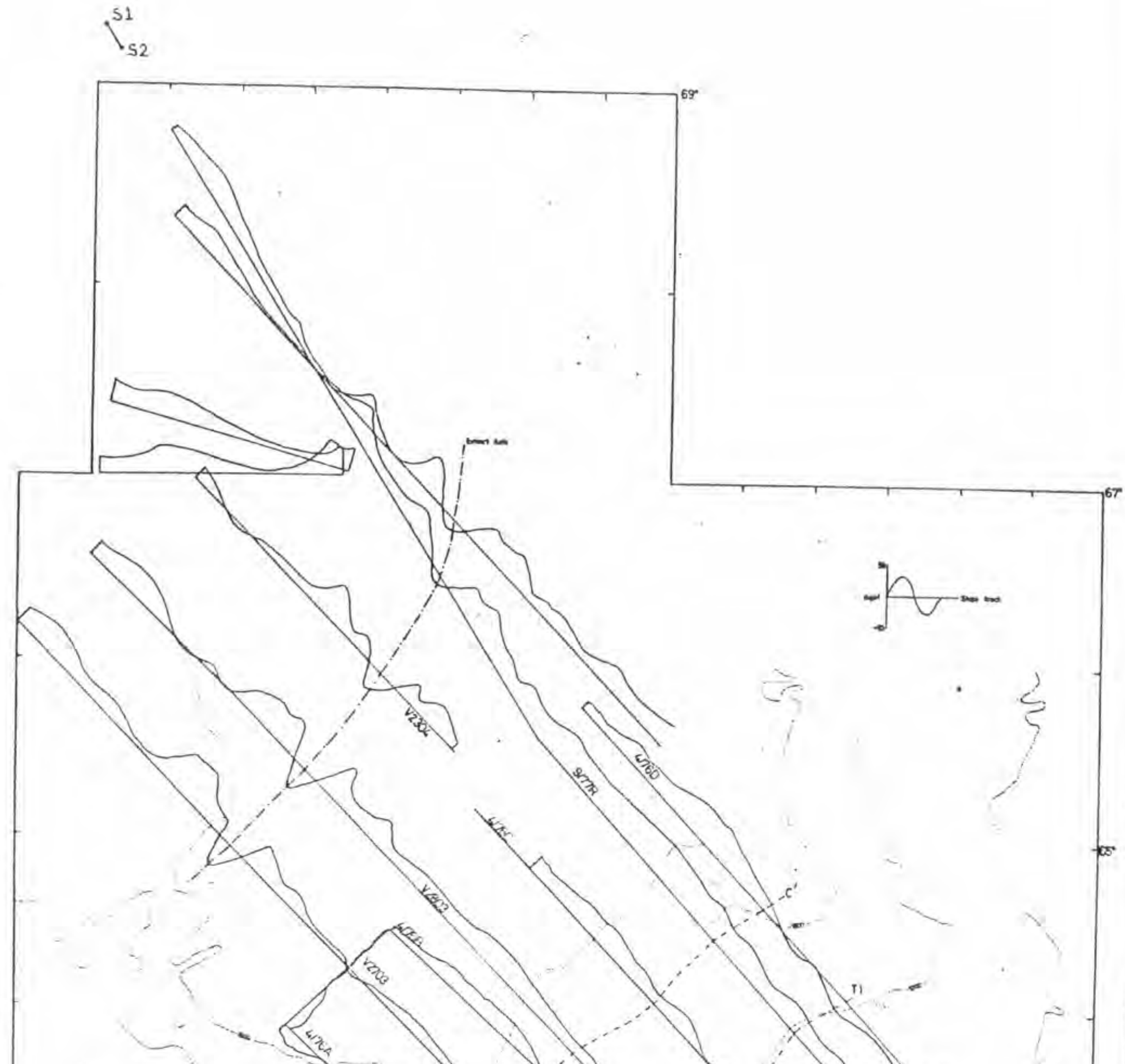

S1
S2
69°
67°
65°
63°
61°
9°W
6°W
3°W
0°
3°E
6°E
V2304
9/77R
4/76D
V2603
V2703
4/76A
C
C'
T1
T2
FAEROES

Figure 3.13 (a)

Profile along line 4/76A showing observed Free Air gravity anomaly, observed magnetic anomaly, crustal model, theoretical Free Air gravity anomaly and theoretical pressure differences.

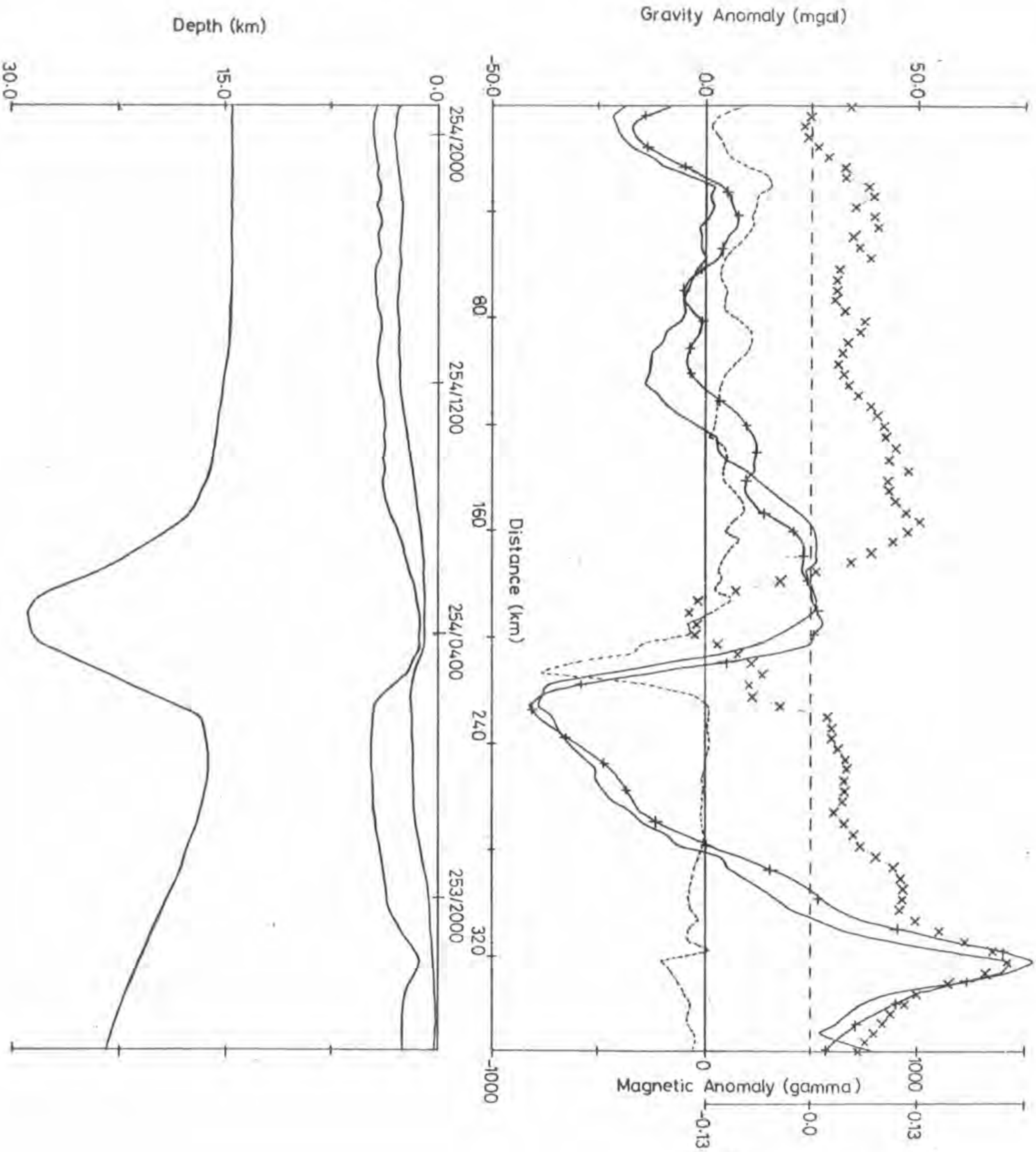
Observed Free Air anomaly

Theoretical " "

Observed magnetic anomaly

× × × × Theoretical pressure differences

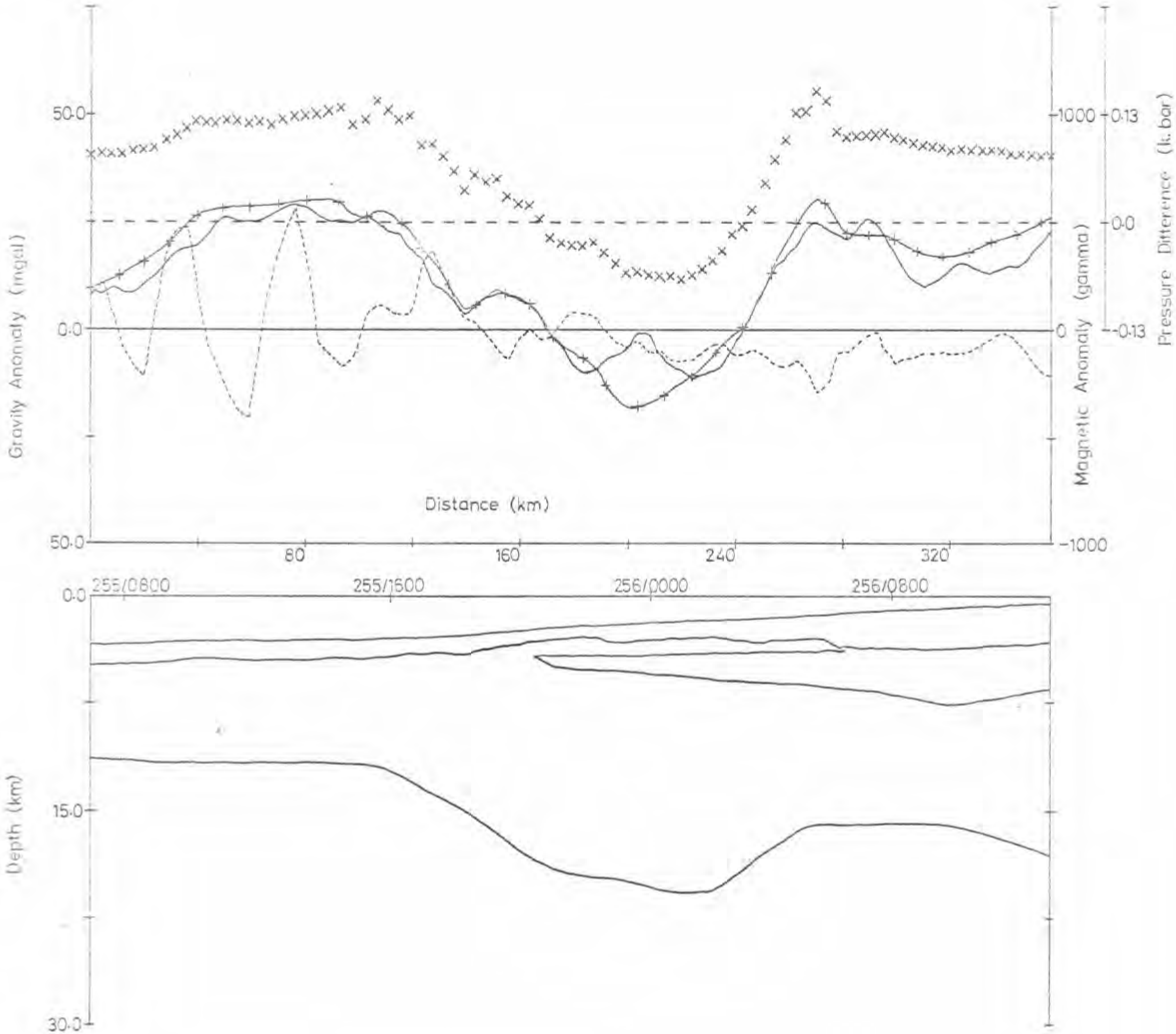
Profile runs from N.W. at (at LHS) to S.E. (at RHS) as do all following profiles.



Gravity Anomaly (mgal)
Depth (km)
Distance (km)
Magnetic Anomaly (gamma)
Pressure Difference (k. bar)
254/2000
254/1200
254/0400
253/2000
-50.0
0.0
50.0
-1000
0
1000
-0.13
0.0
0.13
30.0
15.0
80
160
240
320

Figure 3.13 (b)

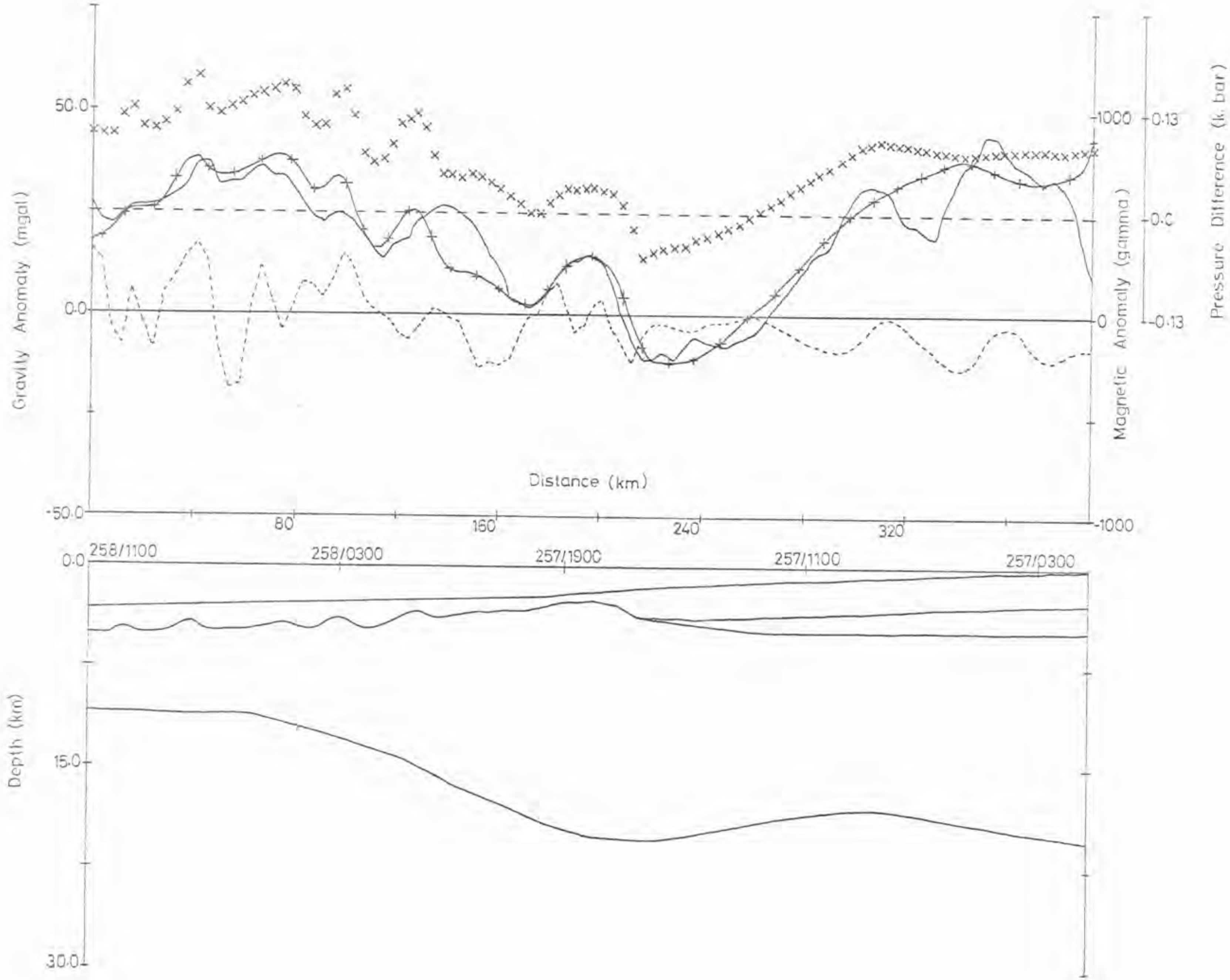
Profile along line 4/76B showing observed Free Air gravity anomaly, observed magnetic anomaly, crustal model, theoretical Free Air gravity anomaly and theoretical pressure differences.
Identification as in figure 3.13 (a)



Gravity Anomaly (mgal)
50.0
0.0
50.0
Distance (km)
80
160
240
320
Magnetic Anomaly (gamma)
1000
0
-1000
Pressure Difference (k. bar)
0.13
0.0
-0.13
255/0800
255/1600
256/0000
256/0800
Depth (km)
0.0
15.0
30.0

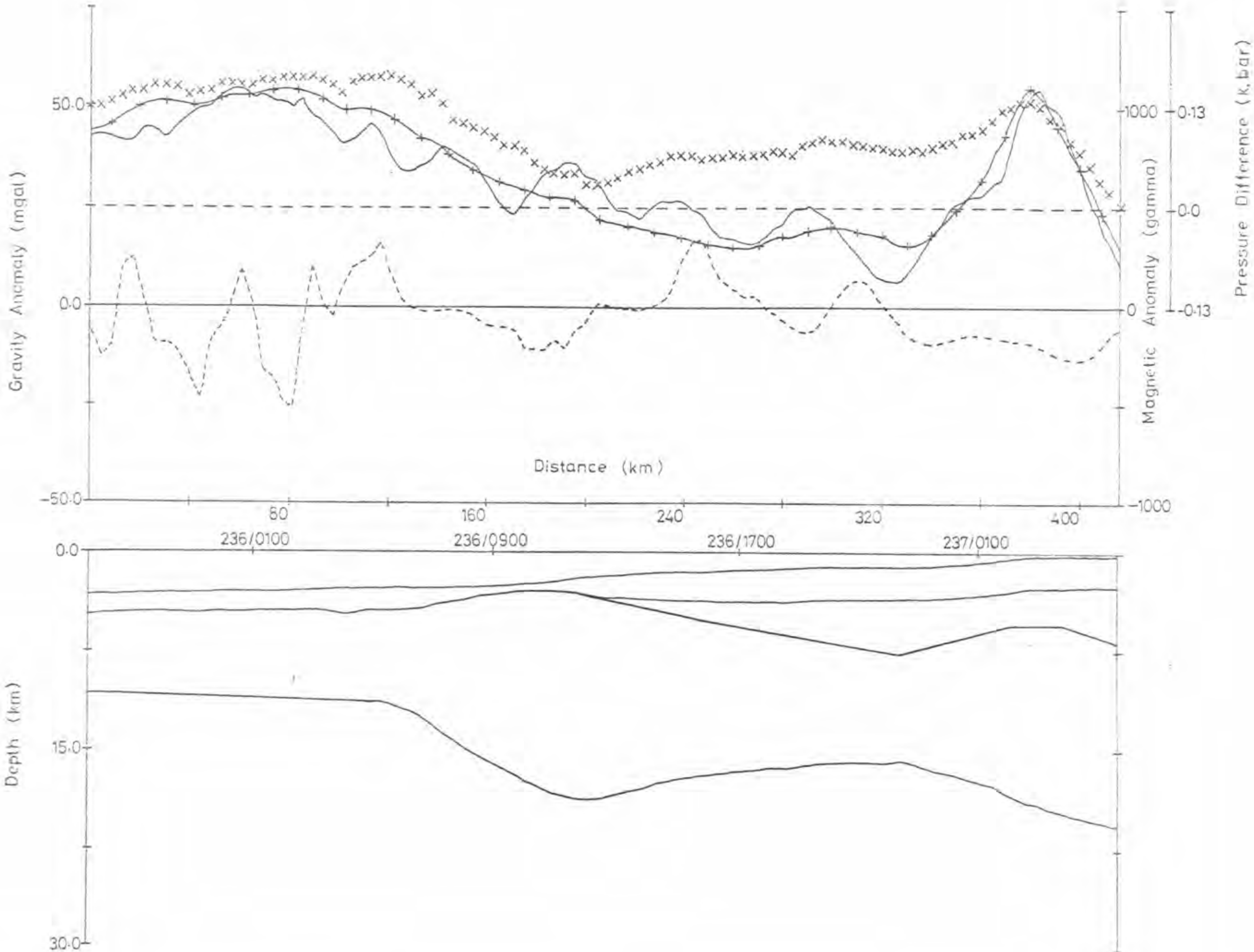
Figure 3.13 (c)

Profile along line 4/76C showing observed Free Air gravity anomaly, observed magnetic anomaly, crustal model, theoretical Free Air gravity anomaly and theoretical pressure differences.
Identification as in figure 3.13(a)



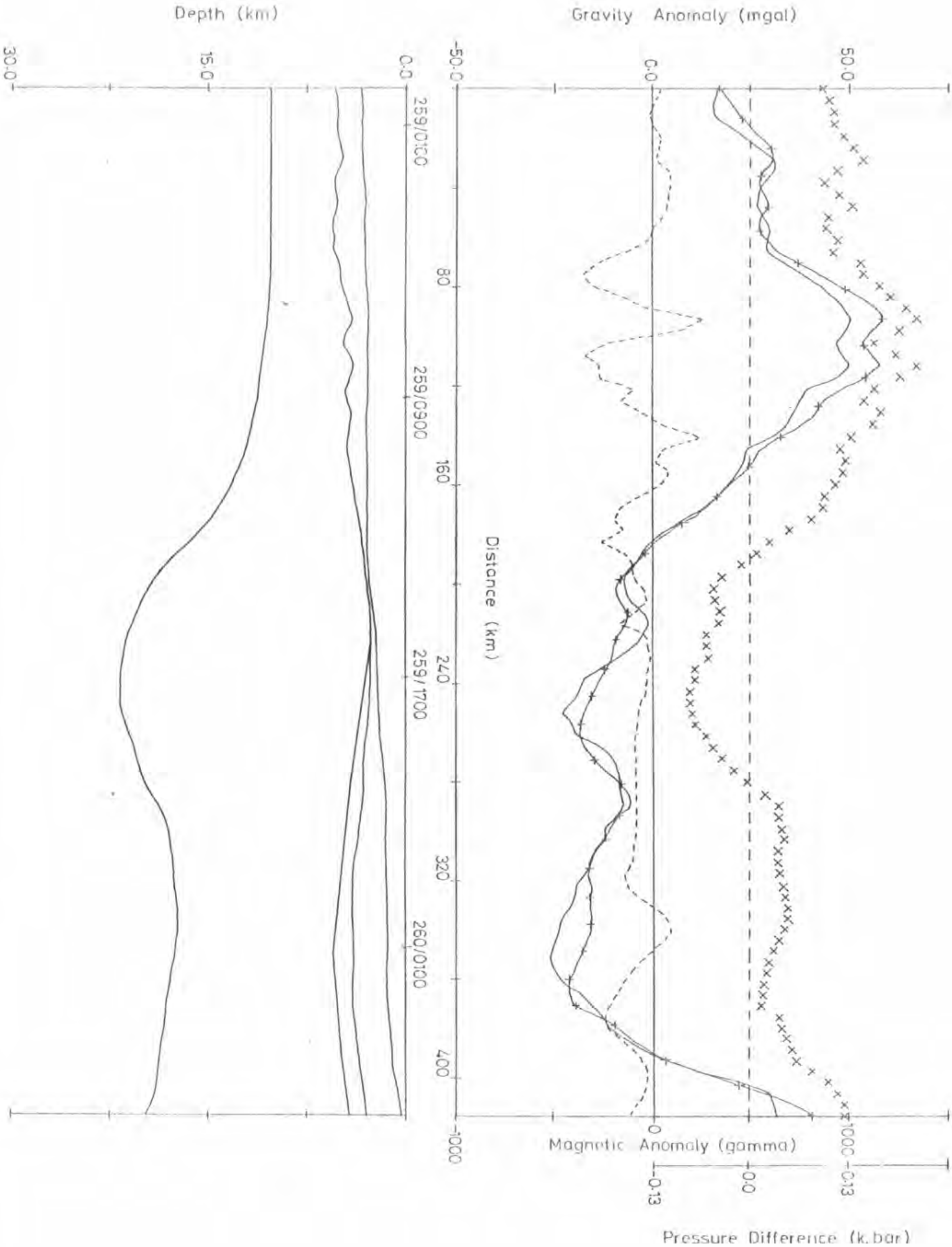
Gravity Anomaly (mgal)
50.0
0.0
-50.0
Distance (km)
80
160
240
320
Magnetic Anomaly (gamma)
1000
0
-1000
Pressure Difference (k bar)
0.13
0.0
-0.13
258/1100
258/0300
257/1900
257/1100
257/0300
Depth (km)
0.0
15.0
30.0

Figure 3.13 (d) Profile along line 9/77R showing observed Free Air gravity anomaly, observed magnetic anomaly, crustal model, theoretical Free Air gravity anomaly and theoretical pressure differences.
Identification as in figure 3.13 (a).



Gravity Anomaly (mgal)
50.0
0.0
-50.0
Distance (km)
60
160
240
320
400
Magnetic Anomaly (gamma)
1000
0
-1000
Pressure Difference (k, bar)
0.13
0.0
-0.13
236/0100
236/0900
236/1700
237/0100
Depth (km)
0.0
15.0
30.0

Figure 3.13 (e) Profile along line 4/76D showing observed Free Air gravity anomaly, observed magnetic anomaly, crustal model, theoretical Free Air gravity anomaly and theoretical pressure differences.
Identification as in figure 3.13(a).



Depth (km)
30.0
15.0
0.0
Gravity Anomaly (mgal)
-50.0
0.0
50.0
259/0100
259/0900
259/1700
260/0100
80
160
240
320
400
Distance (km)
-1000
0
1000
Magnetic Anomaly (gamma)
-0.13
0.0
0.13
Pressure Difference (k.bar)

therefore subject to any error in this velocity estimate. There is a problem on all of the lines in that the base of the shelf sedimentary basin is unknown so it has been chosen such that it is consistent with all known seismic reflection and refraction data and allows the gravity profiles to be modelled.

In constructing these gravity models it has been assumed that all of the variations in the observed gravity field are caused by differences in the structure of the earth above a certain "compensation level", and that below this level the earth is a homogeneous body. It is difficult to determine the depth of this compensation level as any alteration in the depth of the level can be matched by a change in crustal thickness such that there is no variation in the calculated value of gravity. However the western section of the Norwegian Basin traverse crossed the line of a seismic refraction profile beneath which Hinz and Moe (1971) detected the moho at a depth of 10 km. This value was therefore used in calculating the theoretical free air gravity anomaly where the two lines crossed, and the compensation level was then adjusted so that the observed and calculated anomalies were the same. This gave a depth of 27.5 km for the compensation level, and this depth was used in all of the gravity model calculations.

The models shown in figure 3.13 illustrate that the low amplitude, short wavelength anomalies superimposed onto the broad gravity field over the Norwegian Basin are almost entirely generated by the variations in basement topography and sediment thickness revealed by the seismic reflection data. There is a gravity high over the Norwegian Basin which gradually increases northeastwards from around 25 mgal on line 4/76B to about 50 mgal on line 4/76D. On all lines this high decreases over the margin where there is a broad low. The models given in figure 3.13 indicate that this low is caused by a steep thickening of the crust over a short distance immediately to the east of the deep ocean basin. Along those profiles which detected oceanic linear magnetic anomalies (4/76B, 4/76C and 9/77R), the crustal thickening can be seen to take place approximately where the linear magnetic anomalies are replaced by the magnetic quiet zone (figures 3.13 (b), (c), (d)), and on all profiles it takes place seaward of the structural high.

All of the profiles run perpendicular to the Norwegian margin and parallel to the Iceland-Faeroe Ridge. The gravity modelling indicates that the oceanic crust beneath the Norwegian Basin becomes progressively thinner towards the northeast, the depth to the Moho decreasing from 13.5 km beneath line 4/76A to 9.4 km below line 4/76D. The gradient of the moho also decreases northeastwards. These effects are presumably related to the anomalously thick oceanic crust beneath the Iceland-Faeroe Ridge (Bott et. al., 1976), and demonstrate the extensive influence of the ridge.

As noted earlier line 4/76A differs from the other traverses in crossing the northeastern tips of the Faeroes Block and the Faeroe-Shetland Channel. The gravity data demonstrates that a large crustal root must underlie the Faeroes Block with the Moho descending to about 26.5 km below sea-level at its deepest, which is in good agreement with the seismic refraction data from the N.A.S.P. experiment (Bott et. al., 1974). Southeast of the block lies the Faeroe-Shetland Channel. The eastward dipping basement of the Faeroes Block was detected in the seismic records beneath 2.4 seconds of sediments at the western side of the channel (figure 3.4), and therefore in the modelling it has been assumed that at least such a thickness of sediments occurs beneath the entire width of the channel, as the seismic system was capable of detecting basement at any shallower depth. The channel has a free air gravity low but a Bouguer anomaly high which has previously been attributed to a thinned crust beneath the channel (Bott and Watts, 1971), a proposition that is supported by the data from line 4/76A. The exact crustal thickness below the channel cannot be determined from the gravity data alone, as the thickness and density of the sediments within the channel are not known. However, it is not correct to assume that as the sediment thickness is not known then there is no evidence for crustal thinning below the channel, as suggested by Talwani and Eldholm (1972). Indeed, any sediment accumulation within the channel will accentuate the crustal thinning as the sediments have a lower density than the crust, thereby implying that the moho must rise closer to the surface to give the same Bouguer anomaly high. The more sediments there are, the shallower the moho must be. The base of the sediments has not been detected in any published data so the depth of the moho below the channel (15 km) is likely to be a maximum depth. To achieve the same Bouguer anomaly without invoking crustal thinning would require a very large density contrast within the basement, which is considered unlikely.

3.5 Location of the Continent-Ocean Boundary.

Accurate determination of the boundary between the continental crust and the oceanic crust is vital if the geological history and evolution of the Norwegian Basin are to be understood. However it is difficult to provide conclusive evidence as to the position of the boundary without drilling into the crust, so indirect evidence must be used to suggest the location. The following methods can be used to infer the position of the boundary:-

a) The landward termination of the linear magnetic anomalies generated by sea-floor spreading can denote the termination of the oceanic crust, but only if there is no magnetic quiet zone overlying the oceanic material. The boundary can also be denoted by the magnetic anomaly generated by highly magnetized oceanic crust abutting onto weakly magnetized continental crust.

b) The seismic velocity structures of continental and oceanic regions are different, so seismic refraction experiments may sometimes indicate where the change occurs.

c) Seismic reflection profiles across a margin can indicate whether or not there are any changes in the upper crustal structure, and in particular they may show the extent of the oceanic layer 2 if it is sufficiently shallow.

d) It has been suggested by Rabinowitz and LaBrecque (1977) that the continent-ocean boundary may be marked by a characteristic gradient in the isostatic gravity anomaly profile across a margin.

Use has been made of most of these methods in an attempt to locate the boundary in the eastern Norwegain Basin.

To date, all investigations within the southern Norwegian Sea have relied upon the interpretation of Talwani and Eldholm (1972) and there has been little subsequent exploration of the margin, most recent work concentrating instead on the inner shelf area (eg Sellevoll, 1975; Sundvor and Nysaether, 1975). On the eastern side of the Norwegian Basin Talwani and Eldholm discovered a basement high, beneath the base of the continental slope, which terminated in an east-facing escarpment in a similar fashion to a basement high seen beneath the

Vøring Plateau to the north. Seismic reflection profiles appeared to show that the oceanic basement beneath the Norwegian Basin continued eastwards over the high, where seismic refraction experiments detected a high velocity layer close to the sea-bed which terminated at the escarpment, beyond which the profiler records revealed an extensive sedimentary basin. A magnetic high was found to be coincident with the escarpment on all of their traverses, and they claimed that the sea-floor spreading magnetic anomalies are confined to the northwest of the escarpment and that the magnetic high at the escarpment denotes the change from oceanic magnetic anomalies to a marginal quiet zone. They thus concluded that the magnetic data and the structural discontinuity seen in the seismic data indicate that the Faeroe-Shetland Escarpment forms the boundary between oceanic crust underlying the Norwegian Basin and continental crust beneath the continental slope and shelf, ie. that the escarpment marks the site of the initial Tertiary opening of the Norwegian Basin. The high velocity layer seen to the west of the escarpment is therefore attributable to oceanic basement and the entire structural high is an oceanic basement high.

The data from the Durham cruises suggests that the true situation may be considerably different from that proposed by Talwani and Eldholm. The magnetic anomaly chart (figure 3.7) and the magnetic profiles (figure 3.9) show discrepancies between the observed data and the ideas of Talwani and Eldholm. As described earlier, it is possible to identify anomaly 23 and anomaly 24 within the Norwegian Basin, but there is no evidence for anomaly 25, ie. anomaly 24 is the oldest observed anomaly. This is also the oldest observed anomaly seen on either side of the Reykjanes Ridge (Vogt and Avery, 1974) and the Mohns Ridge (Talwani and Eldholm, 1977). Both anomaly 24 and the

Faeroe-Shetland Escarpment are marked on figure 3.7 (the latter being denoted by lineation M1 in figure 3.9) and one can clearly see that these features are over 80 km apart, in contrast to the very short distance between anomaly 24 and Hatton Bank in the eastern Atlantic Ocean (Vogt and Avery, 1974), and between anomaly 24 and Southeast Greenland (Featherstone et. al., 1977). The region immediately west of the Faeroe-Shetland Escarpment is therefore problematical for if, as suggested by Talwani and Eldholm, it is of oceanic origin, the question is raised as to when it was created.

It is also clear from figures 3.7 and 3.9 that the Faeroe-Shetland Escarpment does not mark the seaward limit of the marginal magnetic quiet zone, which is seen to extend to the northwest until it reaches the region of linear magnetic anomalies. The anomaly associated with the escarpment is merely a lineation within the quiet zone. A further point is that one would expect the linear magnetic anomalies to run parallel to the boundary between the continental and oceanic crusts unless there has been either a straightening of the spreading axis after the initial split or oblique spreading has taken place. The Faeroe-Shetland Escarpment and the linear anomalies have distinctly different azimuths so that they converge northeastwards, the distance between anomaly 24 and the escarpment decreasing from about 175 km along line V2703 to about 80 km along line 9/77R.

The new seismic reflection data supports the proposition that there is a structural high beneath the lower continental slope. On all of the profiles it is found that the high occurs between anomaly 24 and the Faeroe-Shetland Escarpment (figures 3.13 (a)-(e)) and that it forms the major structural feature of the region. However, it is seen that the acoustic basement over the high is different from the basement beneath the Norwegian Basin, thereby implying that oceanic layer 2 does not extend over the high. A change in the character of the basement reflector is seen at the seaward base of the high on some profiles.

The crustal models given in figures 3.13 (a)-(e) show that in order to explain the broad gravity low over the margin there must be a rapid increase in crustal thickness immediately to the east of anomaly 24, coincident with the structural high. The structural high is seen to have a distinct crustal root with the moho descending to around 19 km beneath it. It is difficult to see how this is compatible with the proposal that the structural high is oceanic in origin.

Isostatic gravity anomalies were constructed along each of the Durham profiles using the crustal models shown in figure 3.13. These anomalies were generated by calculating the pressure at a specified compensation level beneath each point along the profile and subtracting the pressure calculated at the same depth beneath a continent. A compensation level of 27.5 km was used in all of the calculations. The pressure differences show how much the various features are out of isostatic equilibrium, and are shown plotted along each profile in figures 3.13 (a)-(e). These pressure differences were then converted into isostatic gravity anomalies by varying the depth to the moho along the profile until the pressure difference at each point was zero, calculating the gravity anomaly due to the new model and then subtracting it from the observed anomaly. The isostatic anomalies thus calculated are shown in figures 3.14(a)-(e). The isostatic anomaly profiles all exhibit the steep gradient that is claimed to be characteristic of the continent-ocean boundary (Rabinowitz and LaBrecque, 1977), a similar gradient being shown in

Figure 3.14 (a) Profile along line 4/76A showing observed Free Air gravity anomaly, observed magnetic anomaly, crustal model, isostatic gravity anomaly and theoretical model for perfect isostatic equilibrium.

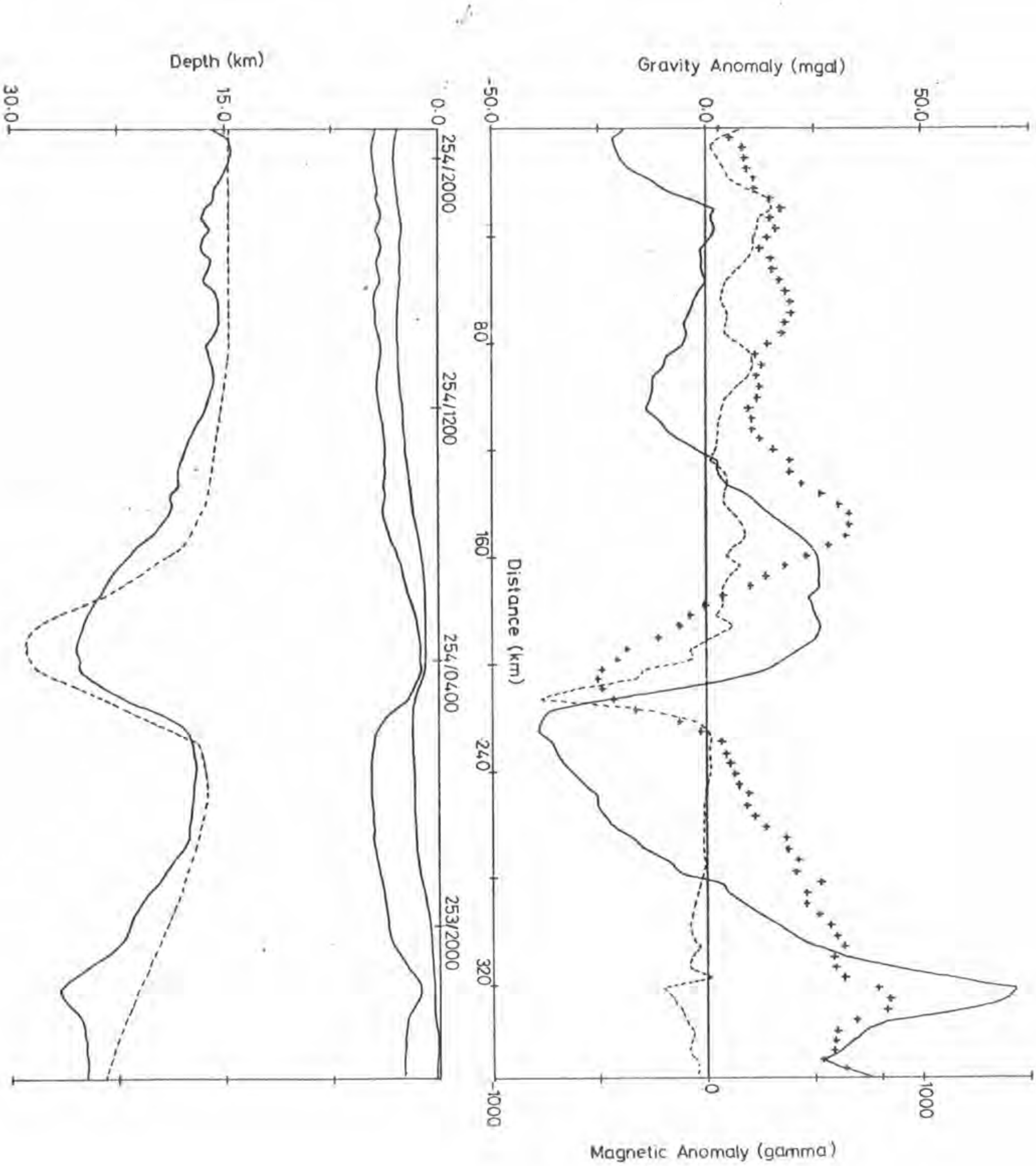
Observed Free Air anomaly.

" magnetic anomaly.

+ + + + + Isostatic gravity anomaly.

\- - - - - - Theoretical moho for perfect isostatic equilibrium.

This & all other profiles run N.W. (LHS) - S.E. (RHS).



Gravity Anomaly (mgal)
-50.0
0.0
50.0
Depth (km)
30.0
15.0
0.0
254/2000
254/1200
254/0400
253/2000
80
160
240
320
Distance (km)
-1000
0
1000
Magnetic Anomaly (gamma)

Figure 3.14 (b)

Profile along line 4/76B showing observed Free Air gravity anomaly, observed magnetic anomaly, crustal model, isostatic gravity anomaly and theoretical model for perfect isostatic equilibrium.
Curves identified as in 3.14 (a).

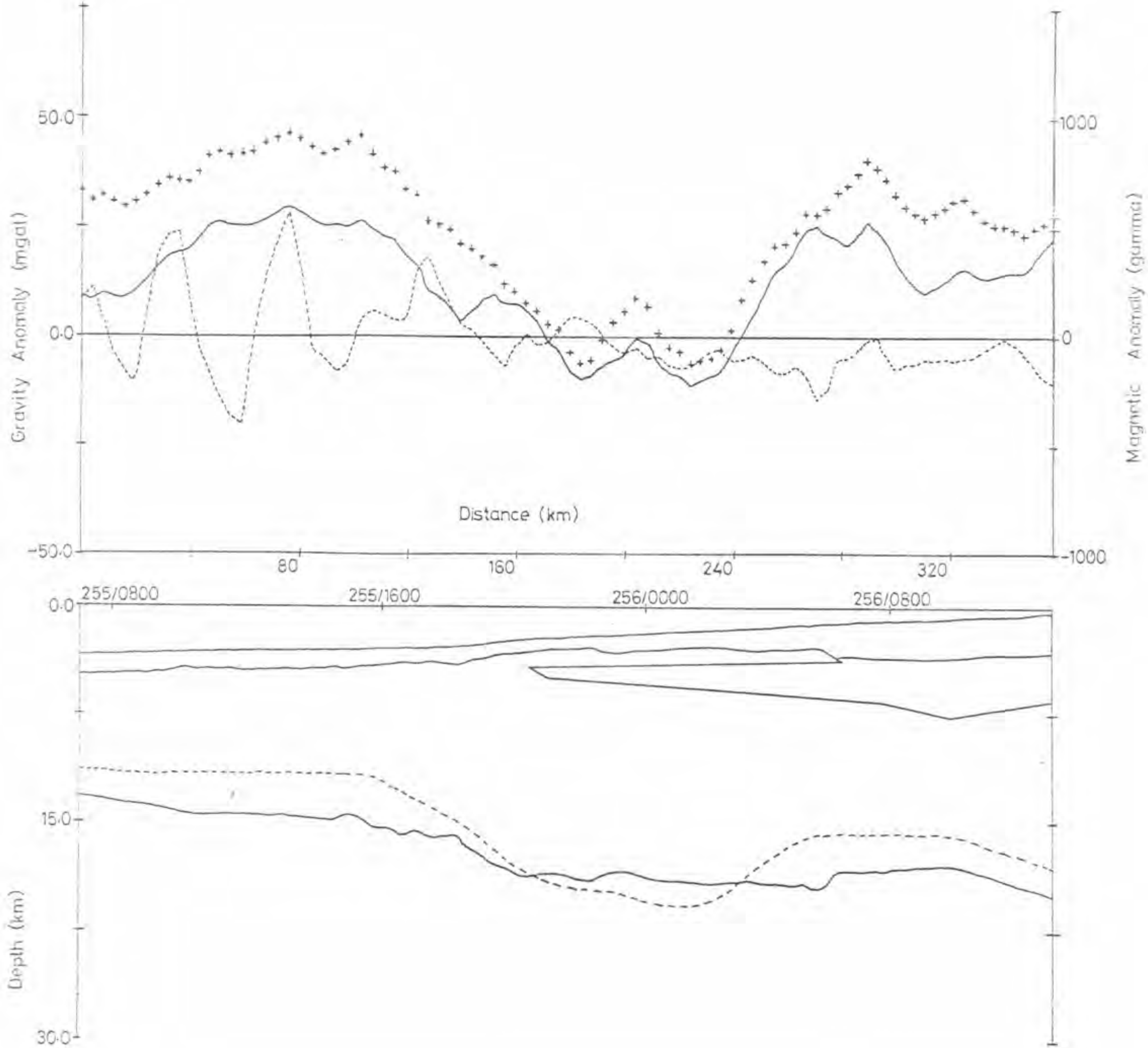

Gravity Anomaly (mgal)
50.0
0.0
-50.0
Magnetic Anomaly (gamma)
1000
0
-1000
Distance (km)
80
160
240
320
255/0800
255/1600
256/0000
256/0800
Depth (km)
0.0
15.0
30.0

Figure 3.14 (c) Profile along line 4/76C showing observed Free Air gravity anomaly, observed magnetic anomaly, crustal model, isostatic gravity anomaly and theoretical model for perfect isostatic equilibrium.
Curves identified as in 3.14 (a).

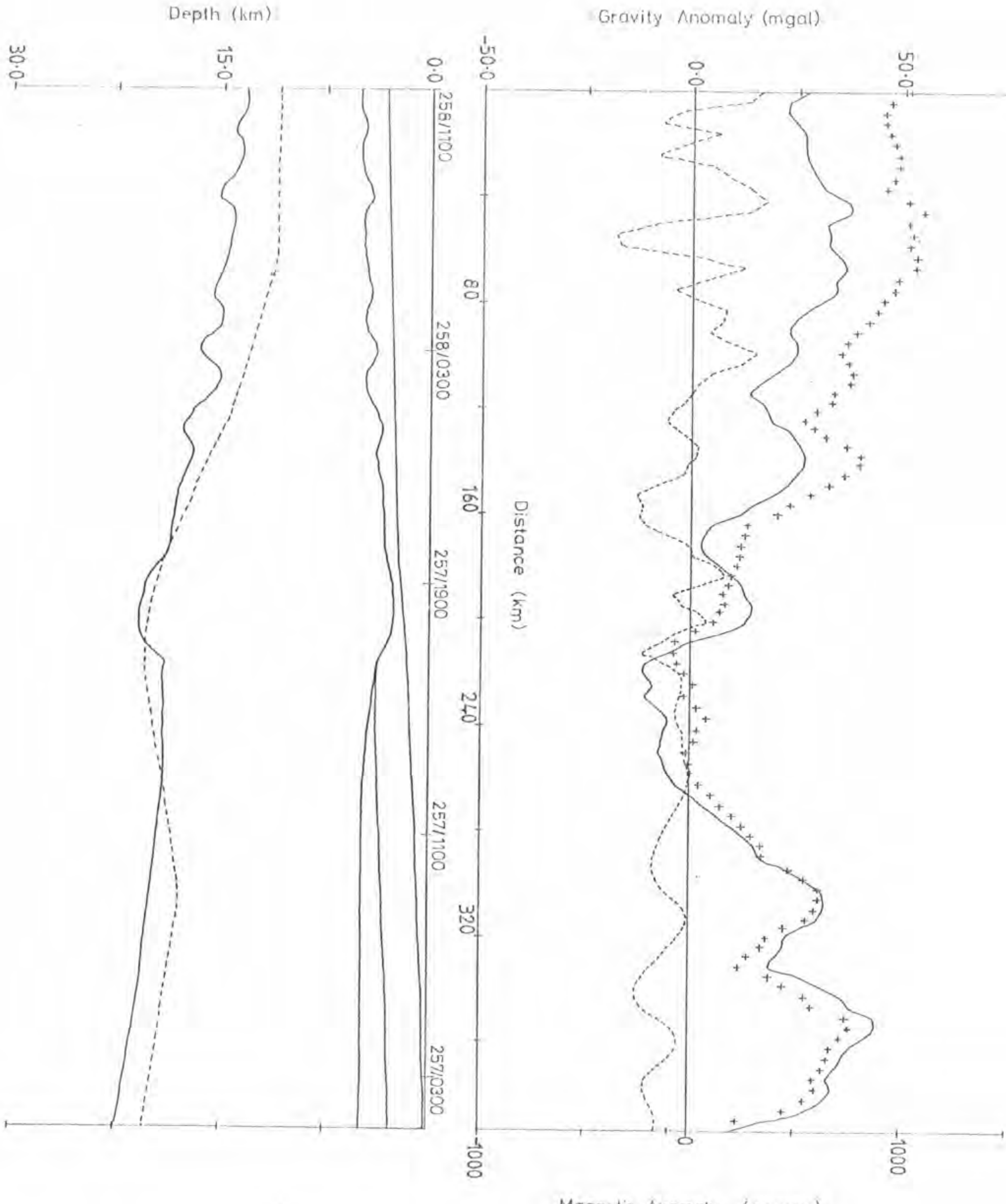

Depth (km)
30·0
15·0
0·0
Gravity Anomaly (mgal)
-50·0
0·0
50·0
258/1100
258/0300
257/1900
257/1100
257/0300
80
160
240
320
Distance (km)
-1000
0
1000
Magnetic Anomaly (gamma)

Figure 3.14 (d)

Profile along line 9/77R showing observed Free Air gravity anomaly, observed magnetic anomaly, crustal model, isostatic gravity anomaly and theoretical model for perfect isostatic equilibrium.
Curves identified as in 3.14(a).

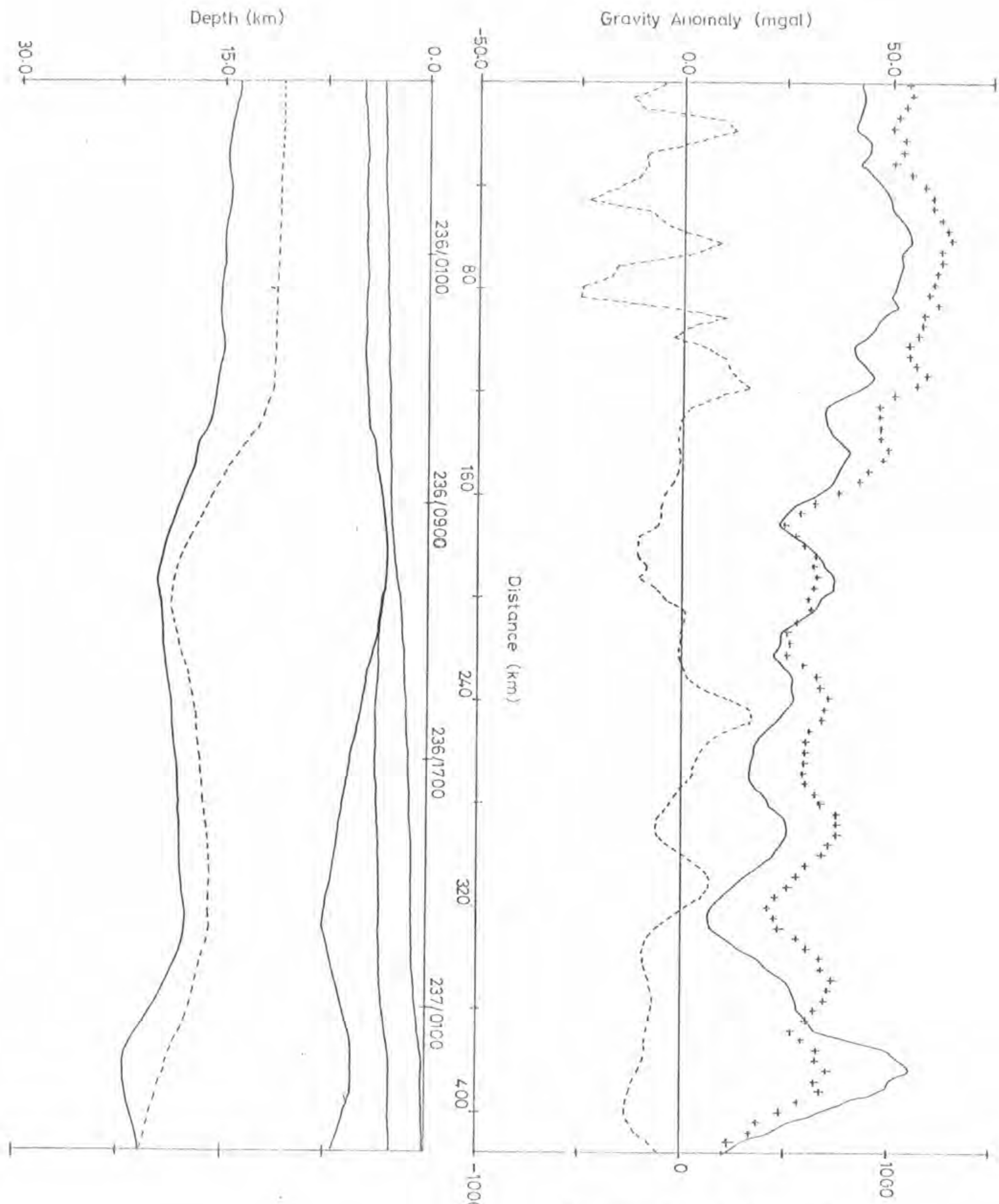
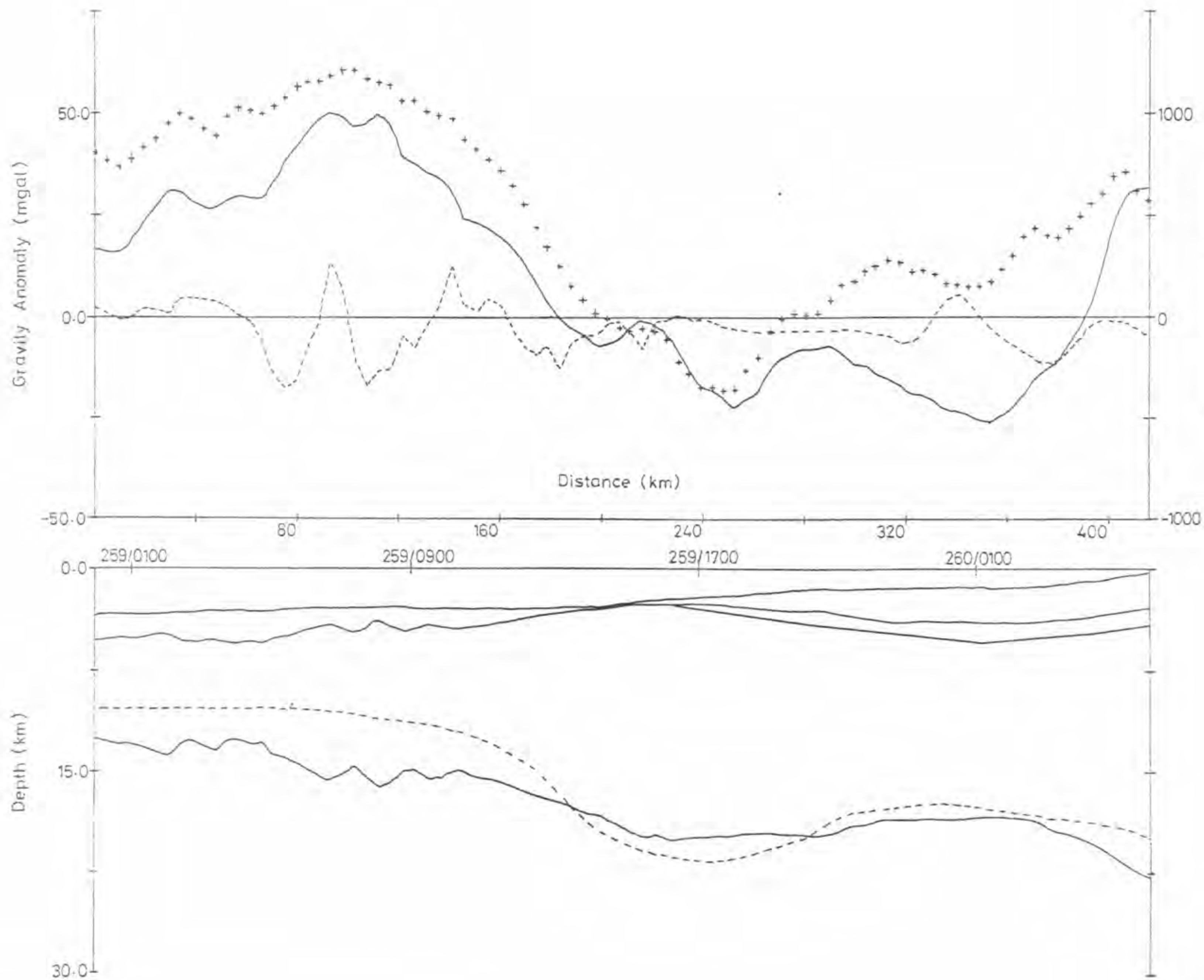

Gravity Anomaly (mgal)
Depth (km)
Distance (km)
Magnetic Anomaly (gamma)
-50.0
0.0
50.0
15.0
30.0
80
160
240
320
400
-1000
0
1000
236/0100
236/0900
236/1700
237/0100

Figure 3.14(e) Profile along line 4/76D showing observed Free Air gravity anomaly, observed magnetic anomaly, crustal model, isostatic gravity anomaly and theoretical model for perfect isostatic equilibrium.
Curves identified as in 3.14(a).



Gravity Anomaly (mgal)
50.0
0.0
-50.0
Magnetic Anomaly (gamma)
1000
0
-1000
Distance (km)
80
160
240
320
400
259/0100
259/0900
259/1700
260/0100
Depth (km)
0.0
15.0
30.0

the pressure differences along the profiles. In all cases (with the exception of profile 4/76A, where the situation is complicated by the presence of the Faeroes Block) the gradients in the isostatic gravity anomaly profiles and the pressure difference profiles occur where the crust thickens and where the magnetic lineations die out. Figures 3.14 (a)-(e) show the moho used to model the free air anomaly and the adjusted moho used in the isostatic anomaly calculations, and it can be seen that the crustal thickening beneath the structural high is steeper than would occur if the margin were in perfect isostatic equilibrium. This disparity is believed to be the true cause of the gradient in the isostatic anomaly profiles, rather than the oceanic basement high proposed as an explanation by Rabinowitz and LaBrecque.

It is therefore suggested that the interpretation of Talwani and Eldholm (1972) must be incorrect, and a different interpretation is proposed. It is postulated that the continent-ocean boundary is not located at the Faeroe-Shetland Escarpment but that it occurs further to the northwest, at the seaward base of the structural high. This suggestion puts anomaly 24 very close to, and parallel to, the boundary, as can be seen in figure 3.7 which shows the postulated boundary marked as the line C-C'. The region between the Faeroe-Shetland Escarpment and the linear oceanic anomalies is therefore of continental rather than oceanic origin, thereby explaining the lack of sea-floor spreading magnetic anomalies over the structural high. The change in the character of the basement reflector is thus due to the change from oceanic layer 2 to continental material at the base of the high. The proposed boundary marks the location where the crust begins to thicken beneath the structural high as the thin oceanic crust meets the thick continental mass. The crust beneath the structural high is thinner than normal continental crust, but this material will have undergone tension and stretching during the initial opening of the region and it is therefore to be expected that it is somewhat thinner than normal.

If the postulated position of the continent-ocean boundary is correct, the Faeroe-Shetland Escarpment must have a different origin to that suggested by Talwani and Eldholm. If the escarpment denoted the boundary, one would expect it to go much deeper than the base seen on the seismic reflection records. However, the density differences across such a feature, with low density sediments abutting onto high density oceanic basement, would generate a large step in the gravity profiles coincident with the escarpment. Such a gradient is not visible on any of the profiles, and one can therefore conclude that the escarpment cannot denote a major structural boundary as previously envisaged and that it does not extend any deeper than the base visible on the reflection profiles. The model of the magnetic anomaly generated by the escarpment (figure 3.11) indicates that the magnetization of the body to the west of the escarpment is of the order of 5 A/m, assuming a thickness of 0.8 km, and as such implies that the body is likely to be of igneous origin. It is suggested that the escarpment marks the termination of a set of lava flows, similar to those found in the Faeroe Isles, which extend over the structural high. Such lava flows would have a smoother surface than the oceanic basement, hence the difference in the reflection character between the oceanic region and the structural high. The high reflectivity of the acoustic basement over the high is thus a result of the contrast between the low velocity and low density of the sediments overlying the lavas, and the high velocity and high density of the lavas. The high velocity layer detected close to the sea-bed west of the Faeroe-Shetland Escarpment in the seismic refraction profiles will therefore be these lava flows, and it is interesting to note that the velocity of the lava as determined by the refraction experiments (5.00-5.20 km/s) is close to the 4.9 km/s velocity of the lavas exposed on the Faeroe Islands (Palmason, 1965).

The lack of a major gradient in the gravity profiles coincident with the Faeroe-Shetland Escarpment limits the thickness of the lava flows to the thickness visible in the seismic records. Therefore the deep sedimentary basin to the east of the escarpment must continue to the west beneath the lavas, possibly becoming progressively thinner to the northwest as illustrated in figure 3.13 (b). The velocity inversion produced, with high velocity lava overlying low velocity sediments, results in the sediments being "hidden" from the seismic refraction experiments. A similar conculsion was reached by Chalmers et. al. (1977) from unpublished data covering the extreme southern section of the escarpment, and they dated the lavas as Palaeocene.

3.6 The Faeroe-Shetland Channel.

According to Talwani and Eldholm (1972) the Faeroe-Shetland Escarpment is separated into two parts, the southern section lying almost coincident with the western boundary of the Faeroe-Shetland Channel, in line with their suggestion that the Faeroes Block is oceanic in origin. The two parts of the escarpment are considered by them to define the eastern boundary of the oceanic crust beneath the Norwegian Basin and tectonically to form a single unit, even though there is no obvious connection between the structures. However, the data described earlier shows that the northern section of the escarpment is not a major tectonic feature and that the continent-ocean boundary lies to the west of the structural high. Moreover Bott et. al. (1974, 1976) have shown that the Faeroes Block is likely to be continental in origin, so it is thought highly unlikely that the southern section of the Faeroe-Shetland Escarpment denotes the continent-ocean boundary. Rather, it is thought that the escarpment marks the edge of the Faeroes lava flows.

The Faeroe-Shetland Channel was crossed by profile 4/76A and the gravity data along this line (figure 3.13(a)) indicates that it is a region of thin crust with a thick sedimentary pile and a shallow moho. Further north there is no seismic evidence for a continuation of the channel, but as the penetration of the seismic system is not very great this is not conclusive. On all of the profiles there is an increase in the free air gravity anomaly landward of the structural high, which is coincident with the sedimentary basin revealed by the seismic data (Talwani and Eldholm, 1972) and the magnetic data (Am, 1970). This is contrary to the normal situation whereby a sedimentary basin creates a gravity low due to the low density of its sediments compared to the basement. Other than invoking a widespread change in the density of the basement, the only way to explain this phenomenon is to propose a thinning of the crust such that the high density mantle material can compensate for the low density sediments and produce the observed gravity anomaly. As with the Faeroe-Shetland Channel the amount of crustal thinning is directly dependent on the thickness of the sediments, which is unknown. However, the moho must rise by at least 2.5 km to compensate for the approximately 70 mgal. gravity anomaly that would be created by the known thickness of sediments. This is illustrated in figures 3.13 (b)-(e) which also show that the crust thickens again southeastwards below the shelf. It is interesting that the distance between the maximum crustal thickness beneath the structural high and the minimum crustal thickness beneath the sedimentary basin is similar on all of the traverses (approximately 90 km, 90 km, 115 km, and 95 km for lines 4/76B, 4/76C,9/77R and 4/76D respectively) suggesting that there is some sort of linear feature rather than a local region of thinned crust. The regions of maximum and minimum crustal thickness have been marked on figure 3.12 as lineations T1 and T2 respectively.

It is seen that the lineations T1 and T2 (figure 3.12) trend northeastwards from the northeastern end of the Fearoe-Shetland Channel. The line of maximum crustal thickness appears to run approximately parallel to the proposed continent-ocean boundary, indicating that the structural high is of almost constant width. As the structural high extends northeast from the Fearoes Block it is thought likely that this feature is a continuation of the block and therefore of the Faeroe-Rockall microcontinent. If the Faeroes Block is continental in origin (Bott et. al., 1974, 1976) then this is a strong argument in favour of a continental origin for the structural high and for the proposed position of the continent-ocean boundary.

The origin of the zone of thin crust is obscure. It could be the result of crustal stretching prior to the splitting of Greenland and Norway giving rise to exceptionally thin continental crust. Alternatively it may be old oceanic crust generated during an earlier abortive spreading event, possibly related to the opening of the Rockall Trough. Bott (1978) has shown that it is possible to account for the opening of the Rockall Trough and the Faeroe-Shetland Channel by a single rotation of the Rockall-Faeroe microcontinent by 2.7^{o} about a pole at 76^{o}N, 90^{o}E. Such a rotation would produce crustal extension to the northeast of the Fearoe-Shetland Channel, possibly resulting in a splitting of the crust and the formation of new oceanic material. The zone of thin crust, as indicated by lineation T2 in figure 3.12, appears to continue northeast away from the Faeroe-Shetland Channel and it may represent the northern extension of the Rockall Trough-Faeroe-Shetland Channel system. It is therefore possible that the rocks with a velocity of around 5.2 km/s found at the base of the shelf sedimentary basin represent oceanic layer 2, or igneous material intruded during the crustal stretching in a similar fashion to the basalts found in the Forties oilfield region (Gibb and Kanaris-Sotiriou, 1976). The opening/stretching in this region presumably ceased at the same time as the Rockall Trough stopped opening, and was followed by the westward migration of the spreading axis. Opening about a new axis to the west separated the structural high leaving it in a similar situation to the Rockall microcontinent. This type of evolution is contrary to the ideas of Eldholm (1978) who considers that there has been no earlier period of normal sea-floor spreading in the region prior to the Cenozoic. In his opinion, Mesozoic crustal extension by down-faulting and graben formation, possibly related to the North Sea phase of crustal tension, is consistent with the data.

3.7 Miscellaneous Topics.

The seismic reflection records from line 4/76D reveal that the steep escarpment visible on the sea-bed at 260/0220 is caused by a vertical fault. The fault has a throw of about 250 mS. and is thought to be a recent feature as it cuts all of the observed reflecting horizons and outcrops on the sea-bed. It may be related to the uplift of Fennoscandia within the last 10,000 years since the removal of the last great ice-sheet. Alternatively it may not be coincidental that it is situated only 20 km to the east of magnetic lineation M2 which has previously been interpreted as indicating the northern continuation of the Great Glen Fault (Avery et. al., 1968). This lineation has no obvious correlation with any seismic feature on any of the profiles, but as the magnetic depth estimates indicate that the cause of the lineation lies within the basement this is not surprising. There does not appear to be any gravity signature associated with the lineation.

A very high gravity peak is seen at the southeastern end of profile 4/76A. This is a continuation of the gravity high detected by Bott and Watts (1971) and interpreted by them as the seaward extension of the Lewisian basement rocks exposed on the Scottish mainland. It has been modelled as a basement ridge (figure 3.13(a)) but could equally well be due to a change in the density of the basement. The seismic reflection data in this region is not good enough to differentiate between the two possibilities.

The rapid decrease in gravity at the southeastern ends of profiles 4/76C and 9/77R is caused by the presence of the Norwegian Channel. It is likely that there is a thicker accumulation of low density sediments within the channel, which has been modelled by adjusting the base of the shelf sedimentary basin.

Chapter 4

The Norwegian Basin

4.1 Introduction.

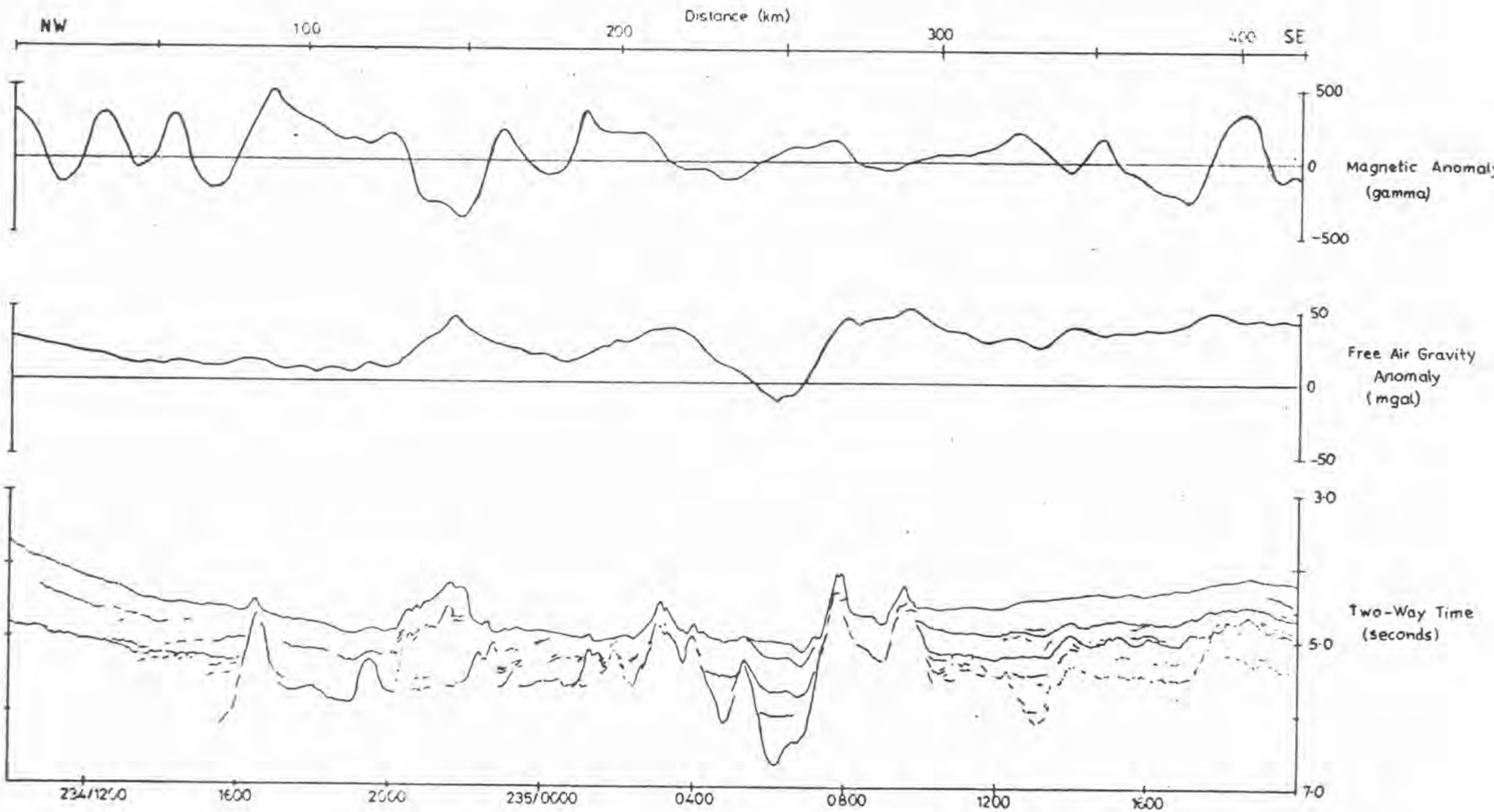
The Norwegian Basin is the name given to that part of the Norwegian-Greenland Sea lying to the south of the Jan Mayen Fracture Zone and to the east of the Jan Mayen Ridge. It is an area that has not been extensively investigated and consequently there is little published data relating to the region. An aeromagnetic map of the basin was published by Avery et. al. (1968), together with an interpretation of the observed magnetic anomalies, and there have been a few two-ship seismic refraction experiments within the area (Ewing and Ewing, 1959; Hinz and Moe, 1971). Recently, however, Talwani and Eldholm (1977) produced a comprehensive evolutionary history of the basin on the basis of data obtained by Lamont-Doherty during several cruises to the region by the R. V. Vema. According to their interpretation the basin was formed by sea-floor spreading that commenced about an axis just to the west of the Faeroe-Shetland Escarpment around anomaly 24 time. Shortly after the initial split between Greenland and Norway the axis is supposed to have jumped westward to the position of the northeast-southwest valley in the centre of the basin, and spreading is thought to have commenced about this axis before anomaly 23 time. Spreading is believed to have taken place about this axis until approximately anomaly 7 time when the axis became extinct. In order to explain the peculiar fan-shaped magnetic anomaly pattern seen within the basin (figure 3.7), Talwani and Eldholm proposed that there must be a complementary oceanic zone, formed by sea-floor spreading between anomaly 20 time and anomaly 7 time, lying to the west of the Norwegian Basin. They suggested that the region immediately to the south of the Jan Mayen Ridge could be the complementary zone. After spreading about the two axes ceased at approximately anomaly 7 time, the spreading axis moved west and sea-floor spreading began about an axis on the Iceland Plateau, splitting the Jan Mayen Ridge away from Greenland. Since that time there has been little tectonic activity within the basin.

A single northwest-southeast traverse across the entire basin was undertaken during the 1977 cruise, gathering magnetic, gravity and seismic reflection data. This chapter will present the data from this traverse and will attempt to relate it to the data obtained along the profiles across the Norwegian margin.

4.2 Seismic data.

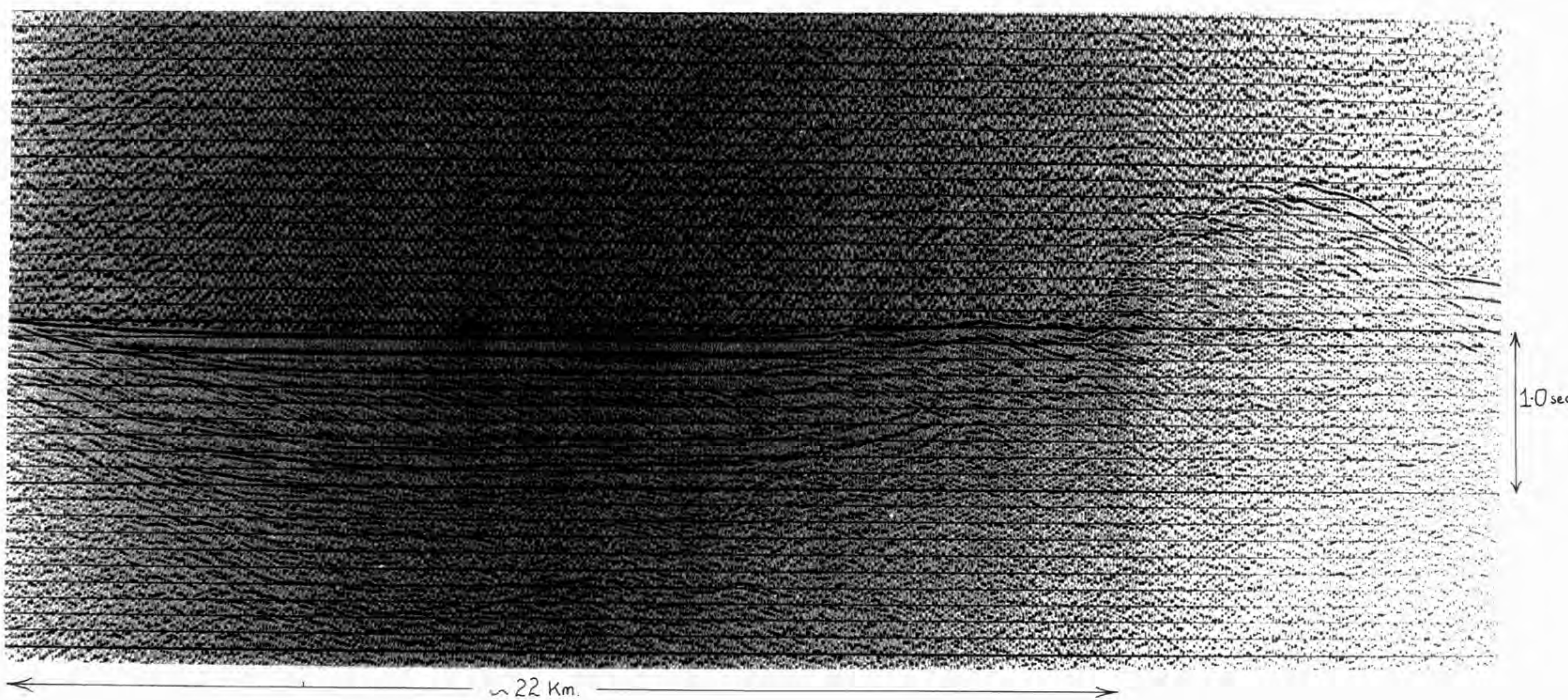
A line drawing of the seismic reflection profile is shown in figure 4.1. This profile reveals the same broad pattern of structures as the profiles presented by Eldholm and Windisch (1974) and by Talwani and Udintsev (1976). In the centre of the basin is a narrow sediment-filled valley that is believed to be the axis of the extinct spreading ridge (Eldholm and Windisch, 1974). The valley is flanked by basement peaks, several of which outcrop of the sea-bed giving the "chain of seamounts" reported by Johnson and Heezen (1967) and by Vogt et. al. (1970 b). There are up to 1.7 seconds of sediments within the central valley while the flanking mountains are typically devoid of sediment cover. The processed record over the central valley is shown in figure 4.2 which also shows the flanking seamount to the east. No internal layering is visible within the seamount, nor is layering seen in any of the other peaks. The mountains are all steep sided (figure 4.2) and the basement rises approximately 2.5 km between the centre of the valley and the flanking peak, a distance of approximately 14 km.

Figure 4.1 Seismic reflection, Free Air gravity anomaly and magnetic anomaly profiles along line 9/77R within the central Norwegian Basin.
The profile runs N.W.-S.E. across the zone of seamounts in the centre of the basin.



Distance (km)
NW
100
200
300
400
SE
500
0
-500
Magnetic Anomaly
(gamma)
50
0
-50
Free Air Gravity
Anomaly
(mgal)
3·0
5·0
7·0
Two-Way Time
(seconds)
234/1200
1600
2000
235/0000
0400
0800
1200
1600

Figure 4.2 Processed seismic reflection section across the central valley, Norwegian Basin, line 9/77R.



1·0 sec
~22 Km.

Some peaks are even steeper than this, eg. the mountain at 234/1600 rises approximately 0.8 km over a distance of about 3 km (figure 4.3).

The central mountainous zone gives way on either side to gently sloping oceanic plains. The acoustic basement in these areas has the rough topography and common diffraction hyperbolae generally associated with oceanic layer 2. On the eastern side of the basin the basement is seen to undulate gently but it does not exhibit the same kind of hummocks seen on line 4/76C which lies immediately to the south (figure 3.1(c)). It is noticeable that in the east of the basin the basement is only poorly visible at a depth of approximately 1.2 seconds beneath two prominent smooth reflectors (figure 4.4). A similar situation exists within the central valley (figures 4.1 and 4.2) with two prominent reflectors overlying the basement, but within the valley the uppermost prominent reflector is relatively shallow.

On the western side of the basin the oceanic basement is clearly seen and there does not appear to be any widespread stratification of the sediments. The difference in the character of the sediments on either side of the basin suggests that they were derived from different sources, and that the central mountainous zone acted as a dam preventing sediments entering the eastern half of the basin from reaching the western side, and vice versa. The high reflectivity of the smooth reflector in the east suggests that this could be the top of a layer of turbidites. Along line 4/76B there is a truncation of a highly transparent sedimentary layer with a highly reflective upper surface at 255/1115, but this is thought to be a local situation as similar structures are not seen on any of the other profiles.

The upper sediments within the western part of the basin sometimes display an easterly dip which is only visible on the processed records.

Figure 4.3 Seismic reflection profile across a basement peak, line 9/77R.
The peak is centred at 234/1630. Note that the airgun ringing is much less prominent on this section than on the 1976 data (eg figure 3.2). The thick black vertical lines form 30 minute time marks.

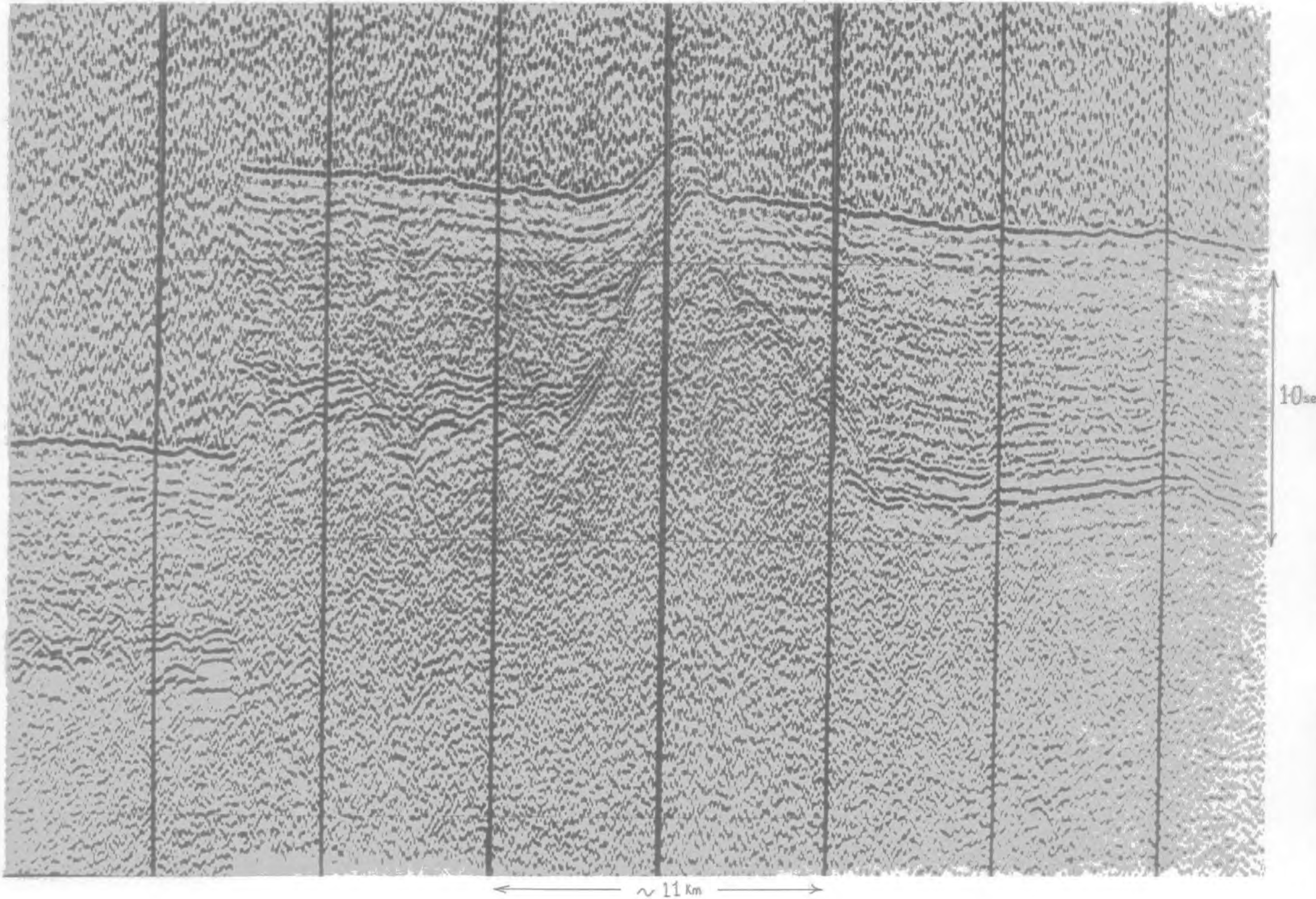
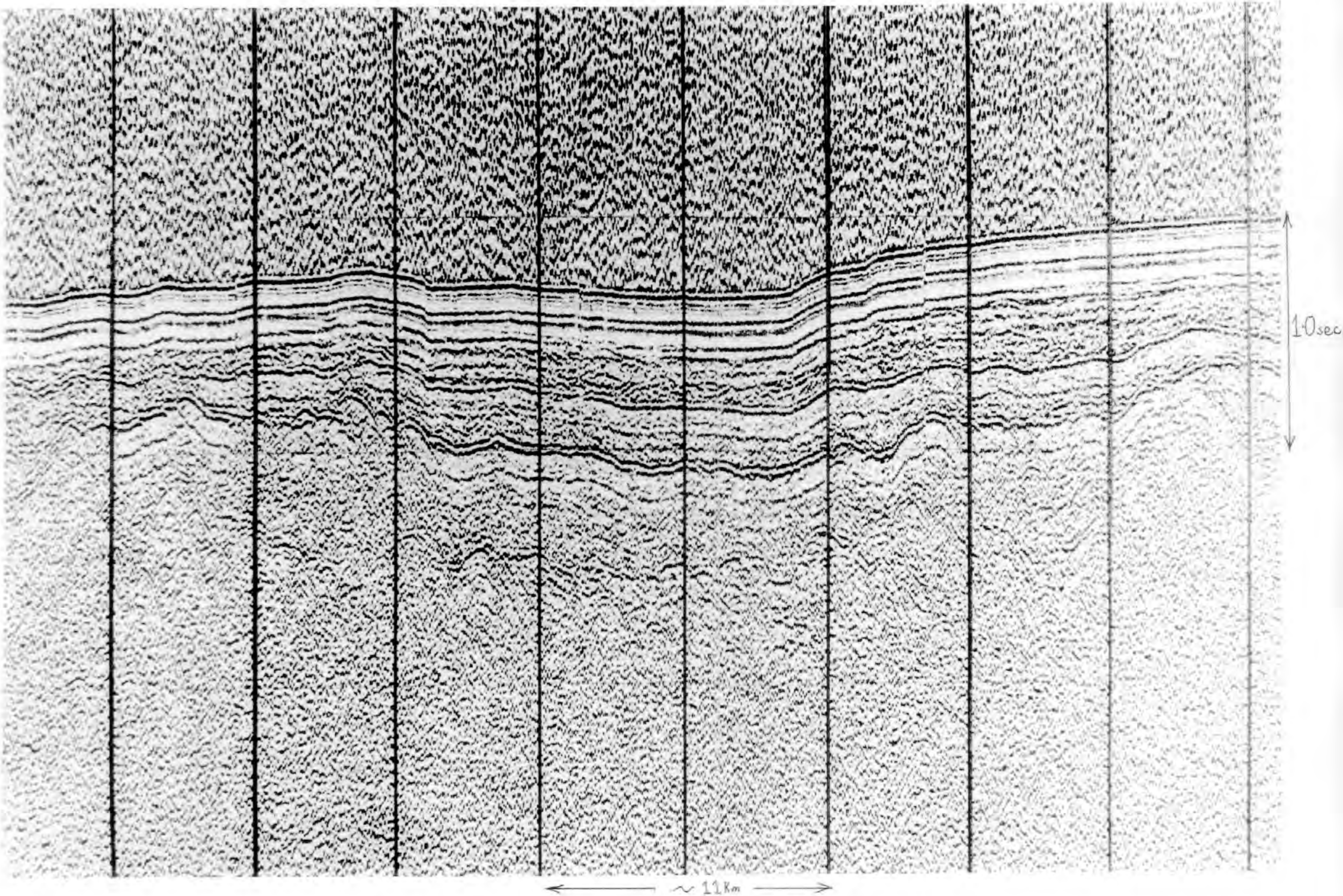

10sec
~ 11 Km

Figure 4.4 Seismic reflection section in the eastern Norwegian Basin, line 9/77R.


1·0sec
~ 11Km

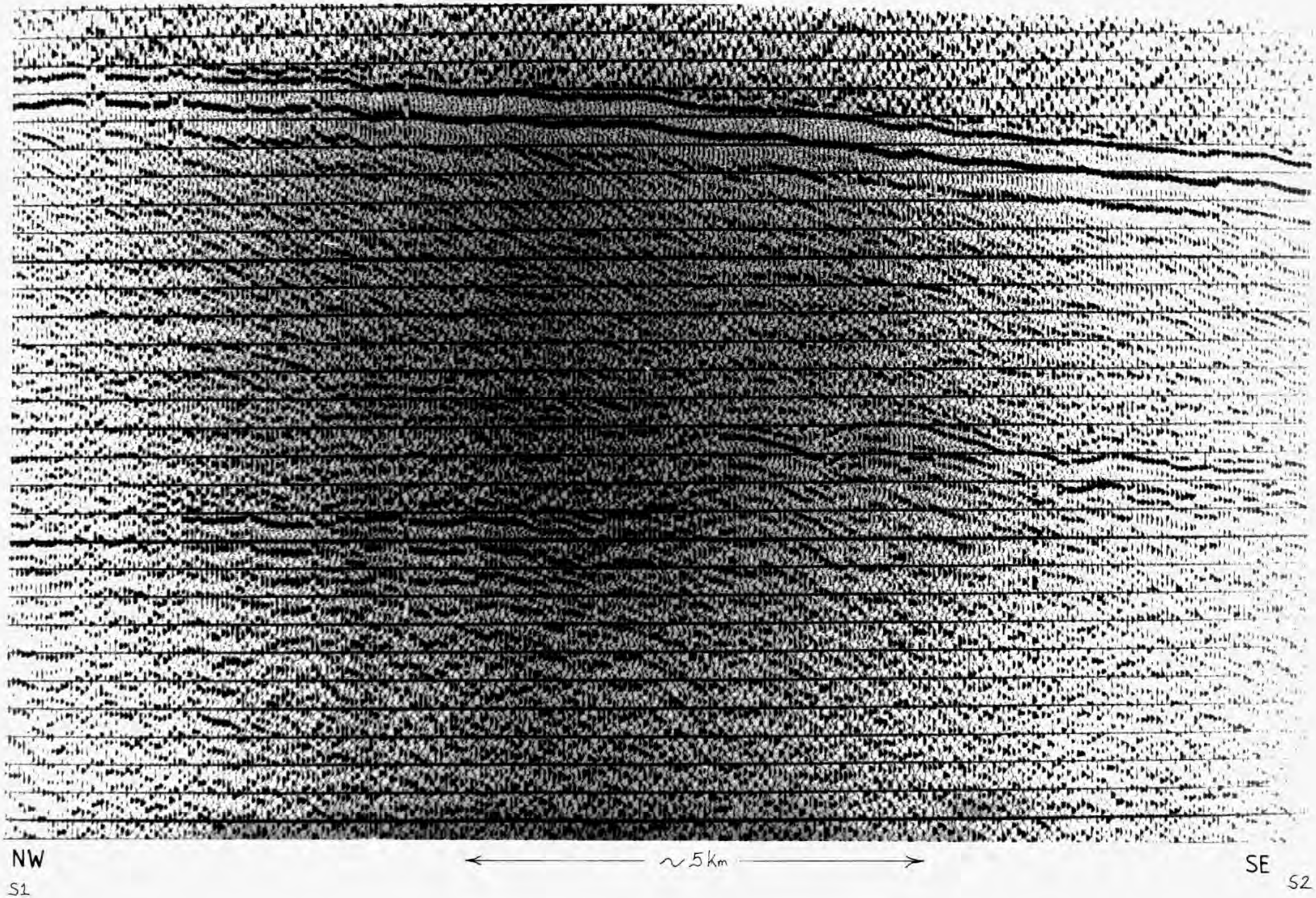
These easterly-dipping sediments are common in the far west of the basin near the eastern boundary of the Jan Mayen Ridge, as shown in figure 4.5. On a few occasions such dipping layers are also seen in the processed records from the eastern side of the basin. It is possible that as these layers are only seen in the processed records then they could be artefacts of the processing, although it is difficult to understand how they could have been produced. If the layers do actually exist they may indicate prograded sediments derived from the surrounding land masses.

In the far west of the basin the oceanic basement is displaced by a step down to the west at 234/0030 (figure 4.5) with an apparent drop of approximately 300 mS. To the west of this step the acoustic basement is much smoother and it is suggested that the step could represent the boundary between the oceanic crust and the continental crust presumed to underlie the Jan Mayen Ridge. A major sedimentary basin exists to the west which appears to continue onto the Jan Mayen Ridge but this is uncertain as the details are masked by multiples. The sediments within the basin reach a maximum thickness of about 2.5 seconds and exhibit considerable stratification, and it is thought that they are likely to have been derived from the Jan Mayen Ridge.

There has been little seismic refraction work carried out within the Norwegian Basin. Ewing and Ewing (1959) gave the results of a two-ship refraction experiment within the area (their station F-9) but this was shot very close to the Jan Mayen Fracture Zone and gave an unusually shallow depth to the moho (7.2 km below sea-level in an area with 3.37 km of water). The only profile to have reliably detected the moho was profile III of Hinz and Moe (1971) which found that the moho lies at a depth of about 10 km beneath the profile. This profile also showed the

Figure 4.5 Processed seismic reflection section from the western Norwegian Basin showing eastward dipping sediments and a basement discontinuity, line 9/77R.

Position of section shown as S1-S2 in figure 3.12.


NW
S1
~5km
SE
S2

existence of oceanic layer 3 with a seismic velocity of about 6.6 km/s at a depth of approximately 6.5 km. Furthermore, Hinz and Moe interpreted their results as indicating the presence of two layers overlying layer 3, the upper sedimentary layer being 0.8 km thick and having a seismic velocity of 2.5 km/s, and the lower layer being 2 km thick with a seismic velocity of between 3.2 and 4.5 km/s. The Durham line 9/77R crossed this profile at approximately 234/1730 and the reflection data also shows the upper sedimentary layer to be approximately 0.9 km thick. However, the reflection data shows that this layer is underlain by acoustic basement which exhibits the roughness and character of oceanic layer 2, which generally has a seismic velocity higher than the 3.2 - 4.5 km/s velocity of the lower layer determined from the refraction data.

Hinz and Moe also carried out a two-ship refraction experiment over the central mountainous zone and concluded that high velocity blocks must rise close to the surface within the seamounts, thereby substantiating the impression that these features are basement peaks. In addition to these two-ship refraction experiments Lamont-Doherty have undertaken several sonobouy refraction experiments within the basin, but they reveal only the detailed sediment structure. A sonobouy experiment was carried out in the eastern part of the basin during the 1977 cruise but this too detected only the sedimentary layers.

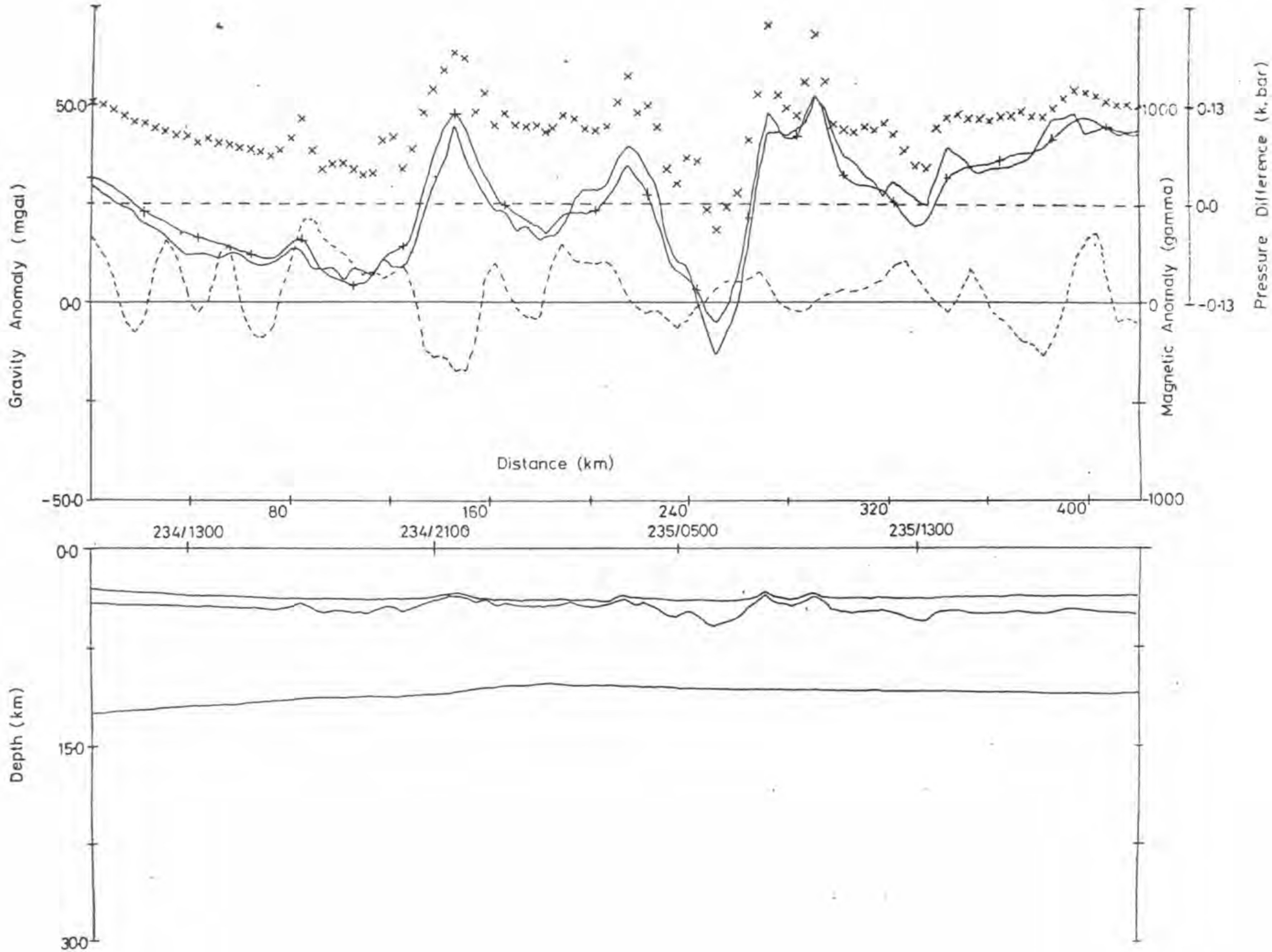
4.3 Gravity data.

The free air gravity anomaly profile obtained along the traverse is shown in figure 4.1 plotted above the seismic section. The principal feature of the profile is the large negative anomaly coincident with the central valley, a correlation noted by Talwani and Eldholm (1977). Further to the south within the basin the central valley is a much more pronounced bathymetric feature and it was by the large gravity anomaly associated with the valley that Talwani and Eldholm were able to trace its northern extension. The anomaly has a minimum of about 60 mgal. relative to the surrounding areas. All the known gravity profiles across the basin are shown in figure 3.12.

Computer modelling of the central and eastern section of the traverse has been undertaken. As with the profiles across the Norwegian margin (chapter 3), the base of the sedimentary sequences has been obtained from the seismic reflection records, and the model assumes a compensation level of 27.5 km. The observed and calculated anomalies are shown in figure 4.6 together with the crustal model used to calculate the synthetic anomaly profile. The model shows that the large negative gravity anomaly in the centre of the basin is solely caused by the large sediment accumulation within the central valley. The short wavelength anomalies superimposed on the general trend can again be seen to be the results of variations in the sediment thickness and basement topography revealed by the seismic reflection record. The gravity data indicates that the moho is at a constant depth beneath the presumed extinct spreading axis and beneath the flanking abyssal plains. Isostatic anomaly profiles were calculated using the methods described in chapter 3 and these show that the central valley has a pronounced isostatic gravity anomaly low as well as a free air anomaly low (figure 4.7).

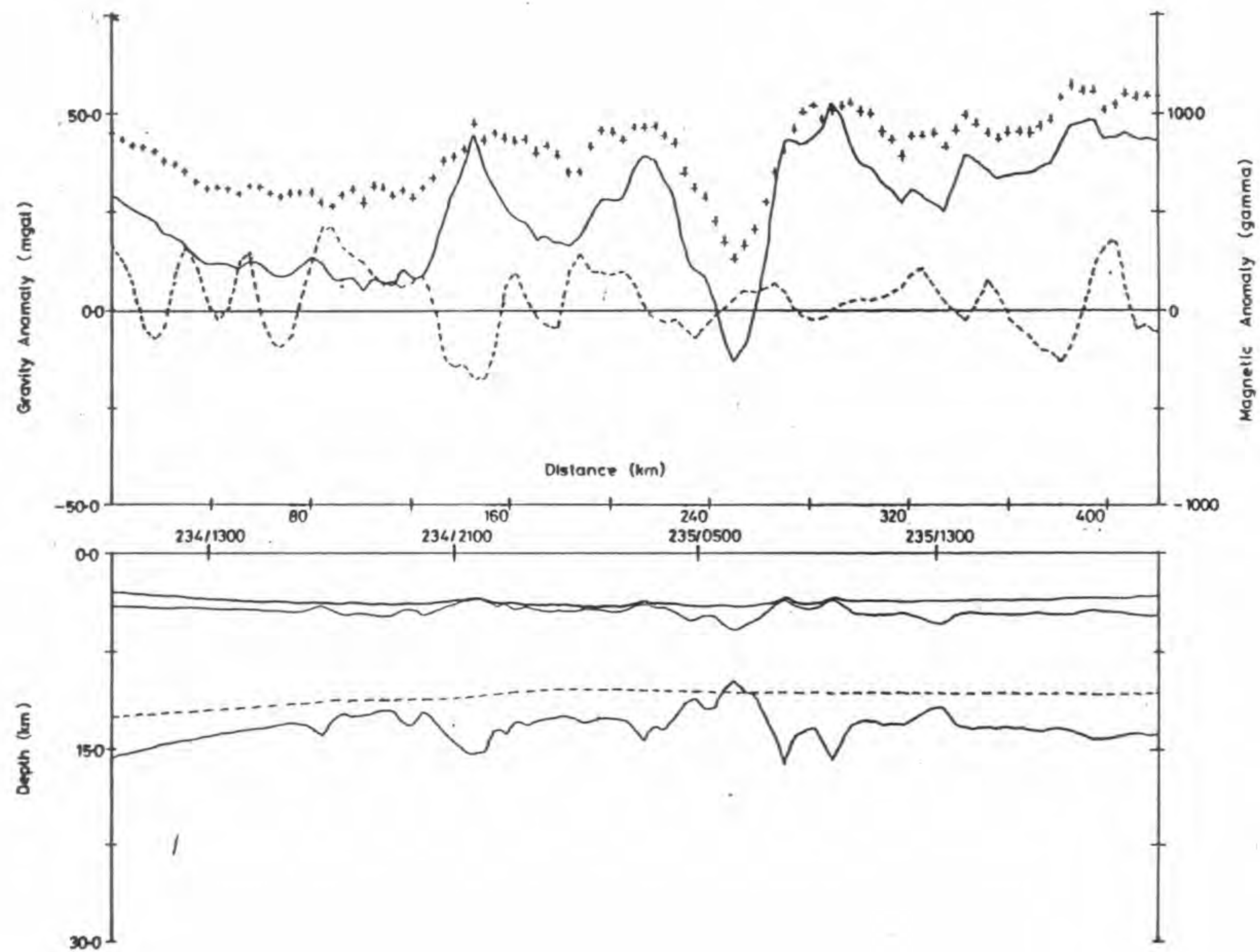
The extreme western section of the profile shows an extensive free air gravity low associated with the sedimentary basin on the eastern flank of the Jan Mayen Ridge. This feature is being studied by Mr A. G. Nunns in conjunction with his investigations of the Jan Mayen Ridge.

Figure 4.6 Profile along line 9/77R within the Norwegian Basin showing observed Free Air gravity anomaly, observed magnetic anomaly, crustal model, theoretical Free Air anomaly and theoretical pressure differences. Identifications as in figure 3.13(a).



Gravity Anomaly (mgal)
50·0
0·0
-50·0
Distance (km)
80
160
240
320
400
234/1300
234/2100
235/0500
235/1300
Magnetic Anomaly (gamma)
1000
0
-1000
Pressure Difference (k, bar)
0·13
0·0
-0·13
Depth (km)
0·0
15·0
30·0

Figure 4.7 Profile along line 9/77R within the Norwegian Basin showing observed Free Air gravity anomaly, observed magnetic anomaly, crustal model, isostatic gravity anomaly and theoretical model for perfect isostatic equilibruim.
Identification as in figure 3.14(a).



Gravity Anomaly (mgal)
50·0
0·0
-50·0
Magnetic Anomaly (gamma)
1000
0
-1000
Distance (km)
80
160
240
320
400
234/1300
234/2100
235/0500
235/1300
Depth (km)
0·0
15·0
30·0

4.4 Magnetic data.

The magnetic anomalies detected along the traverse are shown in figure 4.1 plotted above the gravity and seismic data and in figure 3.7 plotted along simplified ships tracks. The most noticeable features of the magnetic field over the basin are the large amplitude sea-floor spreading anomalies visible on the eastern and western sides of the basin. In the centre of the basin the linear sea-floor spreading anomlies appear to be replaced by a confused magnetic zone with low amplitude anomalies which do not exhibit any obvious orientation. It can be seen in figure 3.7 that the linear anomalies on either side of the basin form a distinct fan-shaped pattern, converging towards the south, and as described in chapter 3, it is possible to identify anomalies 20 - 24 within the eastern half of the basin. Anomalies 18 and 19 may also be present. It is, however, difficult to identify the corresponding anomalies on the western side of the basin. A synthetic anomaly pattern was generated using a model equivalent to that used in identifying the eastern amomalies (figure 3.9) but the observed and calculated anomalies did not match. This work was handicapped by the use of only one profile across the anomalies, but projecting the profiles obtained along the eastern extensions of traverses across the Jan Mayen Ridge (figure 3.7) did not help as these also did not match the synthetic profile, nor did they match the profile along line 9/77R.

The aeromagnetic map of the region (Avery et. al., 1968) shows that the linear anomalies in the west of the basin are more diffuse and less distinct than those in the east, and this is confirmed by figure 3.7. It is also more difficult to identify the western anomalies because, as shown on the aeromagnetic map and implied by figure 3.7, the anomalies exhibit several changes in trend. One of these changes appears to be complementary to the change in trend and lateral offset noted in the anomalies on the eastern side of the basin between lines V2803 and 4/76C (chapter 3) thereby providing additional evidence that there may be a small northwest-southeast fracture zone in this region. The western anomalies have thus been numbered according to the identification of Talwani and Eldholm (1977) and this numbering is shown in figure 3.7.

The absence of linear sea-floor spreading anomalies within the centre of the basin is difficult to understand. Figure 4.1 indicates a correlation between the absence of the linear anomalies and the presence of the basement peaks and seamounts, in that the sea-floor spreading anomalies terminate where the basement peaks appear. In the east of the basin the linear anomalies seem to terminate at 235/1200 along profile 9/77R, immediately to the west of an anomaly tentatively identified as anomaly 18. This correlates with the onset of the seamounts and basement peaks which extend westwards to approximately 234/2000. Linear magnetic anomalies are visible to the west of this position. The solitary basement peak at 234/1600 is separated from the chain of basement peaks by what appears to be normal oceanic basement and it is suggested that this peak is not a part of the central seamount chain. It is puzzling that highly magnetized oceanic basement does not generate high amplitude, short wavelength magnetic anomalies from such undulating topography (assuming that the peaks are formed of oceanic basement). None of the peaks appears to correlate directly with any of the magnetic anomalies, except possibly the peak between 234/2030 and 234/2215 which seems to be associated with a prominent low. There also does not appear to be a magnetic signature associated with the central valley which is thought to represent the extinct axis.

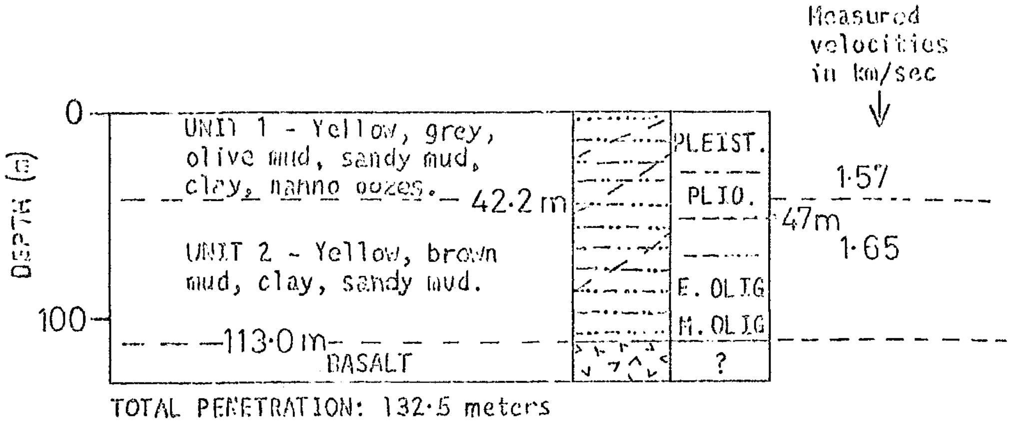
Talwani and Eldholm (1977) have argued that there is an axis of symmetry of the magnetic anomalies which is coincident with the central valley defined by the bathymetric and gravity data. While this appears to be correct in the north of the basin, as illustrated in figure 4.1, it is not true further south. In the south of the basin the eastern linear anomalies are further away from the central valley than those to the west, and they approach the central axis at a shallower angle than the western anomalies. This can be seen in figure 3.7 which shows, for example, that along line V2803 anomaly 21 lies approximately 100 km west of the central valley but the corresponding anomaly on the other side of the basin lies approximately 150 km to the east of the valley. There is no obvious explanation for this difference as the central valley is the only feature that extends across the entire basin and is thus the most likely position of the extinct axis.

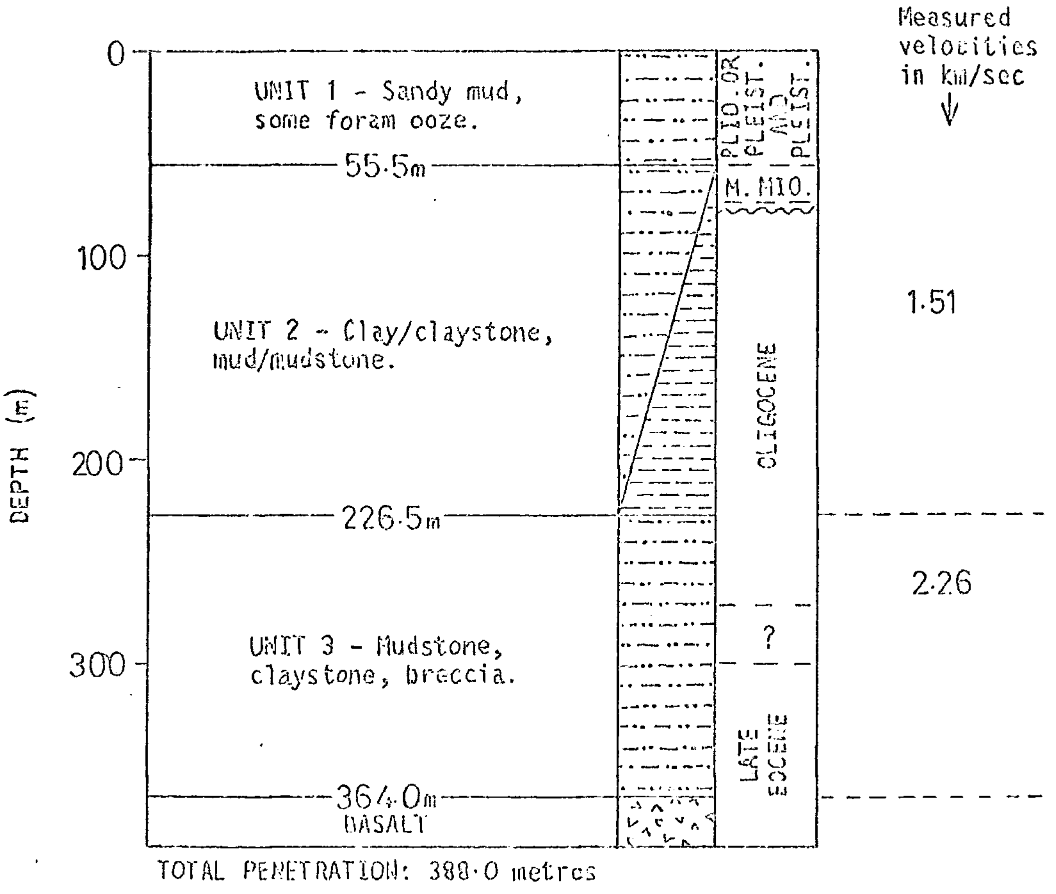
4.5 Drilling Results.

Leg 38 of the Deep Sea Drilling Project was designed to test the theories of Talwani and Eldholm as to the evolution of the Norwegian-Greenland Sea and the surrounding regions. During the cruise the "Glomar Challenger" drilled a hole into the presumed rift mountains immediately to the east of the central valley (DSDP site 337). The intention was to sink the hole as close as possible to the central valley so as to determine the age of the axis, but as the sediment thickness within the valley is quite large a site on the mountain to the east of the valley was chosen. The drilling results are shown in figure 4.8. The hole penetrated 113 m of sediments before reaching a basaltic layer, 19.5 m of which was drilled before drilling was abandonned. The top 47 m of sediments consisted of glacial clays, sandy muds and glacially derived material such as pebbles, below which was found an almost completely pelagic accumulation of clays and muds.

Figure 4.8 Drilling results from D.S.D.P. Site 337.

Figure 4.9 Drilling results from D.S.D.P. Site 350.


Measured velocities in km/sec
0
100
DEPTH (m)
UNIT 1 - Yellow, grey, olive mud, sandy mud, clay, nanno oozes.
42·2 m
UNIT 2 - Yellow, brown mud, clay, sandy mud.
113·0 m
BASALT
PLEIST.
PLIO.
E. OLIG
M. OLIG
?
47m
1·57
1·65
TOTAL PENETRATION: 132·5 meters


Measured velocities in km/sec
0
100
200
300
DEPTH (m)
UNIT 1 - Sandy mud, some foram ooze.
55·5m
UNIT 2 - Clay/claystone, mud/mudstone.
226·5m
UNIT 3 - Mudstone, claystone, breccia.
364·0m
BASALT
PLIO. OR PLEIST.
AND PLEIST.
M. MIO.
OLIGOCENE
?
LATE EOCENE
1·51
2·26
TOTAL PENETRATION: 388·0 metres

The basement consisted of basalt very similar to the tholeiitic basalt typically found in mid-ocean ridge rifts. The presence of several brecciated horizons believed to represent pillow lavas suggested that the basalts at this site had been extruded.

Determination fo the age of the crust at this site has been difficult and the results inconculsive. Silicoflagellates found within the sedimentary layers immediately above the basalt indicate a range of ages from middle Oligocene to late Eocene (29 - 43 M.) but the radiometric ages determined for the basaltic basement are much younger:- 17.5 ± 1.5 M.y. by a Russian group and 25.5 ± 2.4 M.y. by a German group (Kharin et. al., 1976). Magnetically the hole is situated on the western flank of the minimum west of the anomaly tentatively identified as anomaly 18 (45 M.y. on the Heirtzler time scale). Talwani and Udintsev (1976) reconciled these differing ages by assigning the youngest palaeontological age to the site, which is 29 M.y. Then, by using the half-spreading rate of the Mohns Ridge at this time (0.8 cm/yr), they calculated that as the site is approximately 20 km to the east of the central valley, the axis must have become extinct at about anomaly 7 time (27 M.y. ago). This fits the ideas of Talwani and Eldholm (1977) who also suggest that spreading about this axis ceased at about anomaly 7 time.

In order to explain the fan-shaped magnetic anomaly pattern within the Norwegian Basin, Talwani and Eldholm postulated that the region immediately to the south of the Jan Mayen Ridge was created by sea-floor spreading contemporaneous with the creation of the oceanic crust beneath the Norwegian Basin. A hole was drilled into the crust within this area in an attempt to verify this proposal (D.S.D.P. site 350) and the results are illustrated in figure 4.9. The drill penetrated to a depth of 388 m below the sea-bed, of which 362 m was through sediments and the remainder through basaltic basement. Glacial sediments, consisting principally of sandy muds and muds with admixtures of various amounts of volcanic ash and some foraminiferal oozes, were found to extend from the sea-bed to a depth of around 36 m. Below the glacial sediments a lithological unit was defined which extended from 55 m to 264 m. This unit varied from middle Miocene age at the top to Oligocene at the base and consisted of alternating layers of unconsolidated and indurated to lithified sediments, dominantly terrigenous clays and muds. Beneath this layer was found another lithological unit extending down to the basalts at a depth of 362 m. This unit was dominated by lithified sediments, principally mudstones, claystones and breccia. Turbidites were well developed towards the base. The basalt was tholeiitic, but very fresh compared to that from other sites of Leg 38. There is a large scatter in the radiometric dates, but an age of between 40 M.y. and 44 M.y. is indicated, which is not in conflict with the late Eocene age determined palaeontolgically from the overlying sediments, and which also falls within the range of ages suggested for this area by Talwani and Eldholm.

Chapter 5

Conclusions and Discussion

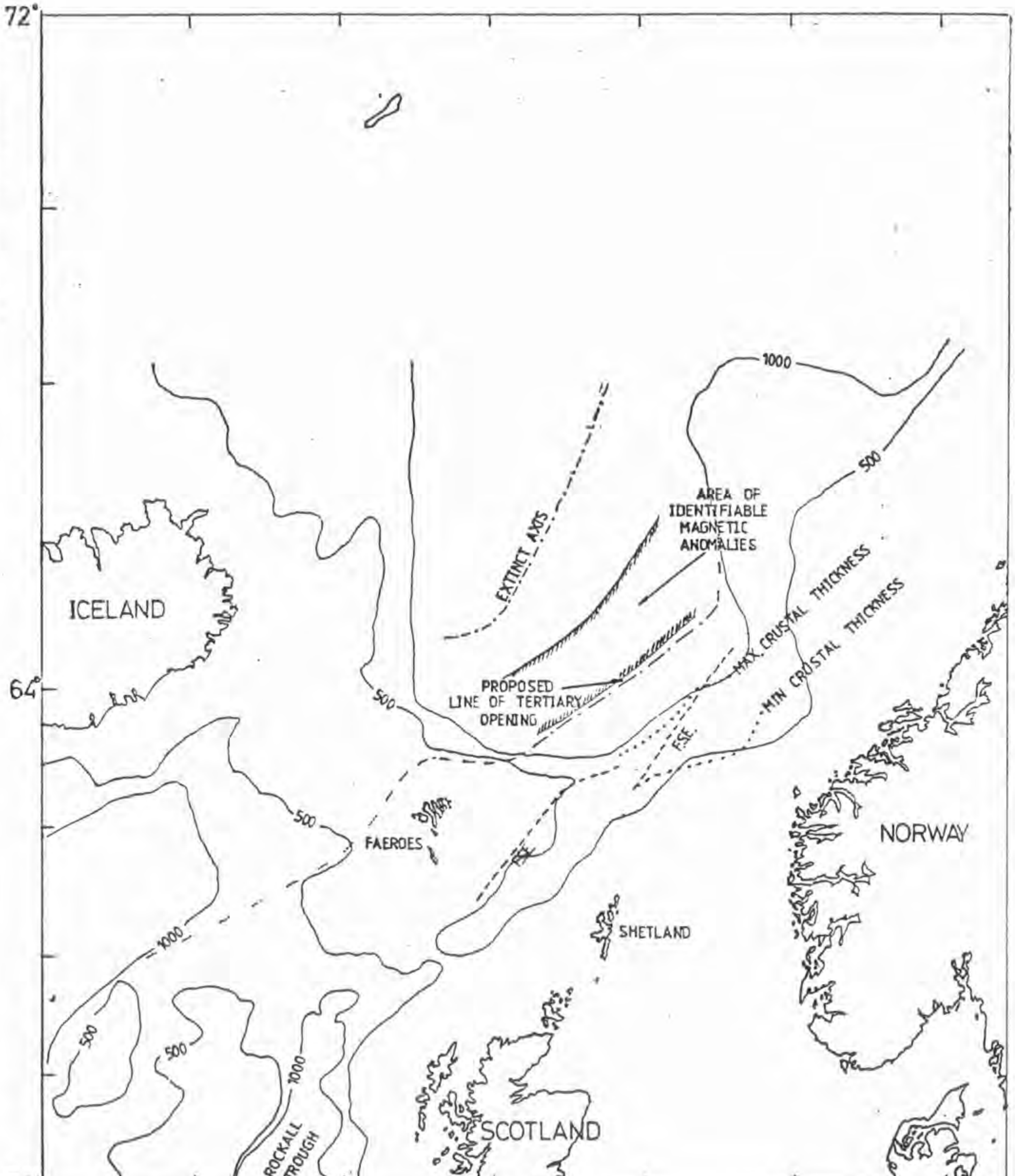
5.1 Introduction.

The structure and evolution of the Norwegian Basin and adjacent areas have been investigated using data gathered during two cruises to the region by the R.R.S. Shackleton together with previously published information. The seismic, magnetic and gravity data suggests that the transition between the oceanic-type crust underlying the Norwegian Basin and the continental-type crust beneath the European continental shelf takes place at the seaward base of a buried, northeast-southwest trending structural high which underlies the lower continental rise west of Norway. Landward of this structural high gravity data indicates the presence of a northeast-southwest zone of thinned crust. It is proposed that this feature be known as the East Shetland Trough. It has been shown that the northern section of the Faeroe-Shetland Escarpment probably results from a landward truncation of a series of Tertiary lava flows and that it does not represent any fundamental structural boundary. The southern segment of the Faeroe-Shetland Escarpment may however represent a major boundary between probable continental crust beneath the Faeroes Block and possible oceanic crust beneath the Faeroe-Shetland Channel. A summary map showing the major features of the area is given in figure 5.1.

5.2 The Location of the Tertiary opening between Greenland and Norway.

If the evolutionary history of the Norwegian-Greenland Sea is to be understood, then it is vital to know precisely where the oceanic and continental crusts meet, as this boundary marks the position of the Tertiary opening of the region. Talwani and Eldholm (1977) have

Figure 5.1 The major features of the northern North Atlantic Ocean and the surrounding areas.


72°
64°
56°
20°
10°
0°
10°
ICELAND
EXTINCT AXIS
AREA OF
IDENTIFIABLE
MAGNETIC
ANOMALIES
1000
500
MAX. CRUSTAL THICKNESS
MIN CRUSTAL THICKNESS
PROPOSED
LINE OF TERTIARY
OPENING
F.S.E.
FAEROES
NORWAY
SHETLAND
ROCKALL
TROUGH
SCOTLAND

proposed that this boundary lies along the two sections of the Faeroe-Shetland Escarpment, and along the Vøring Plateau Escarpment further north. This proposal is based upon their discovery, beneath the lower continental rise west of Norway, of a buried structural high that terminates in an east-facing escarpment that they termed the Faeroe-Shetland Escarpment. Single channel seismic reflection profiles appeared to show that the oceanic basement beneath the Norwegian Basin continued east over the structural high, terminating at the escarpment, while seismic refraction experiments indicated the presence of high velocity rocks close to the sea-bed over the structural high. Talwani and Eldholm suggested that these high velocity rocks represented oceanic basement, in accordance with their interpretation of the seismic reflection profiles. They also found that a characteristic magnetic anomaly is associated with the Faeroe-Shetland Escarpment and they suggested that this anomaly separates the large amplitude, long wavelength sea-floor spreading magnetic anomalies observed within the Norwegian Basin from the extensive magnetic quiet zone observed over the sedimentary basin on the continental shelf. Thus they postulated that the Tertiary sea-floor spreading began immediately to the west of the Faeroe-Shetland Escarpment at approximately anomaly 24 time, and then sometime before anomaly 23 time the axis of spreading jumped west to the site of the extinct axis in the centre of the Norwegian Basin.

The proposals advanced by Talwani and Eldholm were based on the results of a small number of widely-spaced traverses of the southeastern margin of the Norwegian Basin. The data gathered by Durham provides a reasonable good coverage of the area when used in conjunction with the Lamont-Doherty data, and much evidence has been found to suggest that the Norwegian Basin evolved in a manner different to that proposed by Talwani and Eldholm.

The improved coverage resulting from the Durham survey is particularly helpful when consideration is given to the magnetic anomalies detected within the region. The magnetic quiet zone over the shelf sedimentary basin has been found to extend to the northwest of the Faeroe-Shetland Escarpment as far as the sea-floor spreading linear magnetic anomalies, showing that the anomaly associated with the escarpment does not separate two differing magnetic regimes, rather it is an anomaly within the quiet zone. Detailed modelling of the sea-floor spreading anomalies found within the Norwegian Basin has enabled anomalies 23 and 24 to be identified, and it has been shown that anomalies 20 to 24 were created about a single spreading ridge which did not migrate at this stage.

The multi-channel seismic reflection data gathered by Durham shows that the prominent reflector seen over the structural high is not the same reflector as that which forms the basement within the Norwegian Basin, as proposed by Talwani and Eldholm. It has also been found that the seaward base of the structural high coincides with the landward edge of anomaly 24 and with a characteristic gradient in the isostatic gravity anomaly profile across the margin. Thus it is proposed that the transition between the continental and oceanic crusts occurs at the seaward base of the structural high rather than at the northern segment of the Faeroe-Shetland Escarpment.

The northern Faeroe-Shetland Escarpment is interpreted as a shallow feature, as it does not create a large gravity step as would be generated if it did represent the continent-ocean boundary. Detailed gravity modelling and estimates of the depth to the source of the magnetic anomaly associated with the escarpment are in agreement with this, and it has therefore been suggested that the northern Faeroe-Shetland Escarpment is caused by the eastward termination of a series of lava flows which extend over the structural high and over part of the shelf sedimentary basin. These lava flows are the high velocity rocks detected in the seismic refraction profiles and their top surface forms the prominent reflector seen on the seismic reflection records.

Further south the continent-ocean transition is complicated by the presence of the Faeroes Block. The nature and origin of this feature has been the subject of much debate and it is not clear whether the block is continental, as proposed by numerous authors including Bott et. al. (1971, 1974, 1976) and Fleischer et. al. (1974), or whether it is oceanic, as proposed by Zverev et. al. (1976) and Talwani and Eldholm (1977).

The seismic reflection profile obtained along line 4/76A provides evidence that the Faeroes Block and the Norwegian Basin are fundamentally different. On this profile a prominent reflector beneath the Basin, interpreted as the top of oceanic layer 2, is seen to abut onto the deep structure of the Faeroes Block, and the character of the basement beneath the Block is seen to be different from that beneath the Basin. This has been taken as indicating that the Faeroes Block is continental in nature.

The position of the continent-ocean boundary to the south of line 4/76A is uncertain. A direct southwestward continuation of the boundary proposed to the north would cross the Faeroes Block to the southeast of the Faeroe Islands, passing close to the line where Bott et. al. (1974) detected a major change in crustal velocity. However, the Faeroes

Block appears to be a single tectonic unit and it is considered unlikely that such a fundamental boundary passes through the block. Thus it is suggested that the boundary changes direction south of line 4/76A, to run approximately east-west along the base of the bathymetric escarpment which forms the northern boundary of the Faeroes Block. The boundary then turns southwest along the bathymetric scarp between the Iceland-Faeroe Ridge and the Faeroes Block, as proposed by Bott et. al. (1971, 1974, 1976) and Fleischer et. al. (1974), and continues southwestwards along the western edge of the Rockall-Faeroe microcontinent (Vogt and Avery, 1974). The line of opening proposed within this thesis is similar to that used by Bott and Watts (1971) in their pre-drift reconstruction of the continents around the North Atlantic, and it indicates that the southern segment of the Faeroe-Shetland Escarpment does not denote the Tertiary continent-ocean contact. This feature is discussed further in section 5.3.

The Faeroe-Shetland Escarpment has been likened to the Vøring Plateau Escarpment (Talwani and Eldholm, 1972, 1977; Sellevoll, 1975), an escarpment which crosses the Vøring Plateau in a northeast-southwest direction (figure 1.2). Both escarpments have little or no bathymetric expression, high velocity rocks are present close to the sea-bed to the west of both features and large sedimentary basins exist to the east of them. Close inspection, however, reveals that the two escarpments are not similar features. It has been shown that the northern section of the Faeroe-Shetland Escarpment is not a major structural feature but is likely to be the edge of a series of Tertiary lava flows which extend over the structural high and part of the sedimentary basin. In contrast, the Vøring Plateau Escarpment marks a basement step, with the basement to the west of the escarpment having a higher elevation than that to the east. This is shown by the magnetic data (Am, 1970), the seismic reflection and refraction data (Talwani and Eldholm, 1972, 1977) and by the drilling results from Leg 38 of the Deep Sea Drilling Project (Talwani and Udintsev, 1976). There is also a pronounced drop in the Free Air gravity anomaly coincident with the escarpment (Grønlie and Talwani, 1978) caused by the change in basement elevation. Such a step is not seen at the northern Faeroe-Shetland Escarpment.

Multichannel seismic reflection data (Hinz and Weber, 1976) has shown the presence of reflectors beneath the strong shallow reflector interpreted as the top of the oceanic basalts on the outer Vøring Plateau, and, while the drilling results from Leg 38 of the D.S.D.P. confirm the differences in basement elevation across the escarpment, they do not provide conclusive evidence that the outer Vøring Plateau is oceanic in origin, as suggested by Talwani and Eldholm (1972). Thus it is suggested that the northern Faeroe-Shetland Escarpment and the Vøring Plateau Escarpment may be fundamentally different features. The Vøring Plateau Escarpment denotes the position of a major structural boundary but it is not certain whether it marks the transition between the continental and oceanic crusts.

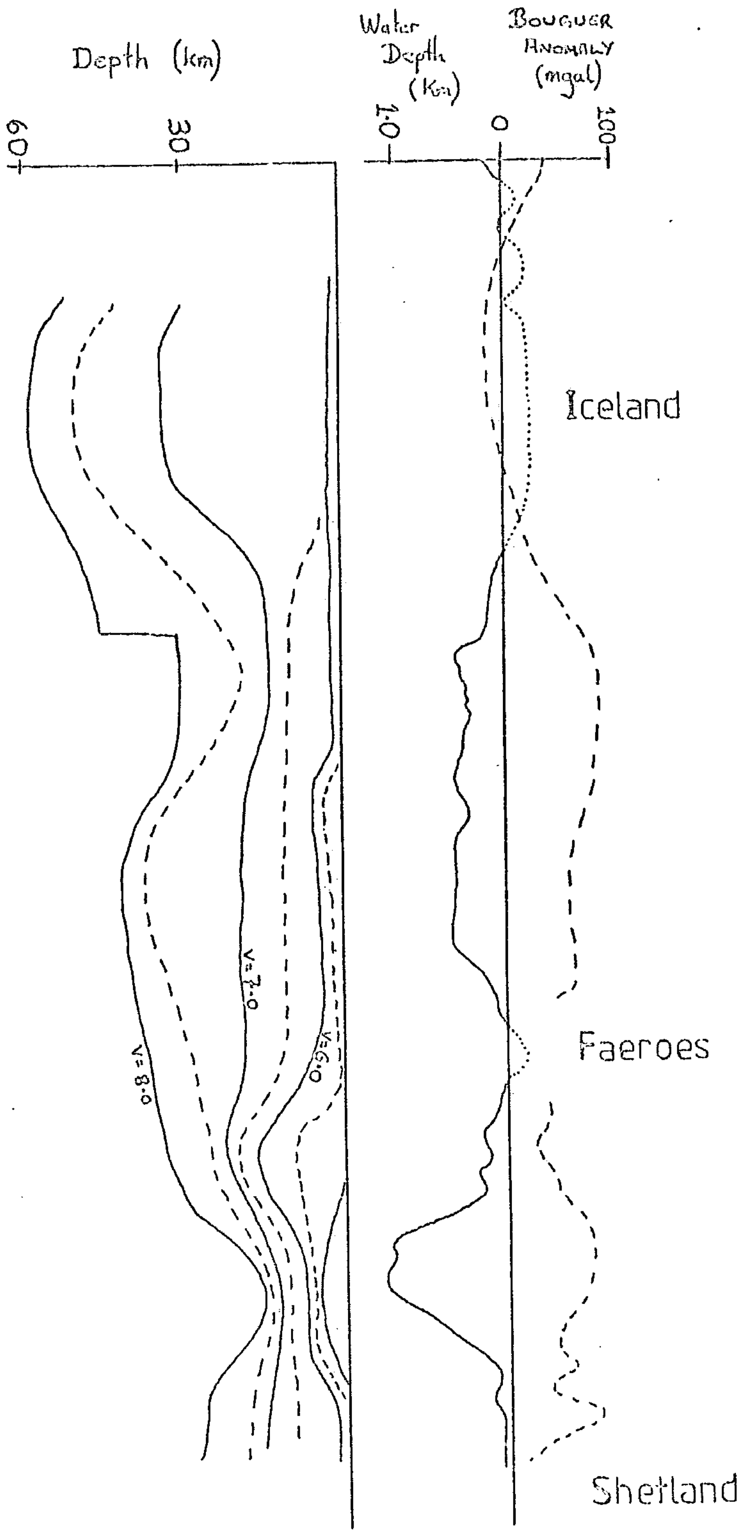
5.3 Pre-Tertiary Evolution.

The history of the region prior to the Tertiary rifting between Greenland and Eurasia is not well determined, but there is evidence to suggest that the Tertiary opening was not the first rifting episode to have affected the area. The Rockall Trough is generally believed to have been created by sea-floor spreading (eg. Scrutton and Roberts, 1971; Hallam, 1971; Bott, 1975b) and the trend of the isobaths implies that the Faeroe-Shetland Channel formed as a continuation of the

Trough. Further to the east there was extensive graben formation (possibly indicative of incipient sea-floor spreading) in the North Sea during the Jurassic and early Cretaceous, eg. the Viking Graben, which is known to be underlain by a relatively thin crust (Ziegler, 1975). A seismic refraction line across the Vøring Plateau (Hinz, 1972) was interpreted as showing the presence of high velocity material, possibly the upper mantle, beneath a thin, possibly oceanic, crust underlying the Inner Vøring Plateau. It has also been suggested (Whiteman et. al., 1975) that the Rockall Trough, Faeroe-Shetland Channel, Viking Graben and the Vøring and Stadt Basins form a linked rift system and that at sometime there existed a proto triple-junction northeast of the Shetlands, although there is no published evidence to show that these features meet, or even extend as buried features beyond their known positions.

It has been shown (Bott, 1978) that the opening of the Rockall Trough can be accounted for by a rotation of the Rockall-Faeroe microcontinent away from N.W. Europe by 2.7° about a pole of rotation at 76°N 90°E. Such a rotation also results in the opening of the Faeroe-Shetland Channel, confirming the impression gained from inspection of the bathymetric contours that the Faeroe-Shetland Channel is a northward continuation of the Rockall Trough. Thus, it is felt that the interpretation of the gravity data from line 4/76A in terms of a thinned oceanic crust beneath the Faeroe-Shetland Channel is justified, and this interpretation is supported by the seismic refraction data (Zverev et. al., 1976) as shown in figure 5.2. However, a rotation of the Rockall-Faeroe microcontinent as suggested by Bott results in a wider Faeroe-Shetland Channel than that defined by the bathymetric contours, the western boundary of the proposed rift

Figure 5.2 Seismic refraction profile between the Shetland Isles and the Iceland-Faeroe Ridge. Redrawn from Zverev et.al. (1976).


Depth (km)
60
30
Water Depth (Km)
1.0
0
100
Bouguer Anomaly (mgal)
Iceland
Faeroes
Shetland
V=8.0
V=7.0
V=6.0

passing close to the line where Bott et. al. (1974) found a major change in the crustal velocity beneath the Faeroes Block. It is possible that the bathymetric contours on the western side of the Faeroe-Shetland Channel, which define the southern section of the Faeroe-Shetland Escarpment, denote the southeastern limit of the Tertiary lava flows and that the transition from the continental Faeroes Block to the oceanic Faeroe-Shetland Channel lies further west, obscured by the great thickness of the lavas.

A further implication of the opening of the Rockall Trough by the rotation of the Rockall-Faeroe microcontinent is that there ought to exist a northeastern extension of the Faeroe-Shetland Channel. This must lie either to the northeast of the present Faeroe-Shetland Channel or along the east coast of Greenland, separated from the Faeroe-Shetland Channel by a northwest-southeast fracture zone running along the northern edge of the Greenland-Iceland-Faeroe Ridge. The zone of thinned crust found beneath the lower continental rise to the east of the structural high, and termed the East Faeroes Trough in this thesis, is the first evidence that this postulated extension of the Faeroe-Shetland Channel may exist, and that it is situated on the Eurasian side of the Norwegian-Greenland Sea rather than on the Greenland side. This feature runs northeastwards from the Faeroe-Shetland Channel beneath the continental rise, separating the structural high from the Norwegian continental shelf. It may continue into the Stadt Basin and possibly to the Inner Vøring Plateau but this has not been investigated due to a lack of data. The structural high is possibly a continental fragment and it is suggested that it forms the northeastern extension of the Rockall-Faeroe microcontinent.

If the East Faeroes Trough does represent the northern extension of the Rockall Trough and the Faeroe-Shetland Channel then it must have been formed at the same time as these features. Therefore if this proposal is correct the oldest sediments within the East Faeroes Trough must post-date the opening of the Rockall Trough. The time of opening of the Rockall Trough has not been conclusively determined but if it was created by sea-floor spreading then the absence of linear magnetic anomalies, together with the fitting of the continents about the Atlantic further south, suggests that the Trough may have opened during the period of constant magnetic polarity in the Cretaceous, although Russell (1976) has suggested a Permian opening. Thus if the sediments within the East Faeroes Trough are older than this, then either the Trough formed earlier than the Rockall Trough and the Faeroe-Shetland Channel and not as part of that system, or the Rockall Trough and the Faeroe-Shetland Channel formed much earlier.

Some of the seismic refraction experiments within the region appear to indicate that the sedimentary layers within the East Faeroes Trough are underlain by a refractor with a velocity of about 5.2 km/s which occurs at a depth of between 4.2 km and 6 km below sea-level (Grønlie and Talwani, 1978). This is the deepest refractor that has been found and it may represent the top of the oceanic basement underlying the Trough. If this refractor is the top of the oceanic layer 2 then, assuming that the basement was formed during the mid-Cretaceous, a sedimentation rate of around 0.05 mm/year would be needed to accumulate the observed thickness of sediments. Such a rate of sedimentation is not inconsistent with the rate of Tertiary sedimentation within the northern North Sea.

The seismic velocities detected in the refraction experiments can also be used to infer the ages of the sediments within the East Faeroes Trough, although this is rather uncertain. It has been found in the southern North Sea that Tertiary sediments rarely have velocities greater than 2.25 km/s (Hornabrook, 1967; Wyrobek, 1969), so it is tentatively suggested that sediments which exhibit seismic velocities in excess of 2.5 km/s are of Mesozoic age. The seismic refraction profiles indicate that there is a thin layer of rocks, about 0.75 km thick, which have a velocity of around 3.50 km/s and which directly overlay the 5.2 km/s layer. It is suggested that this layer, which is the deepest layer detected on most of the refraction profiles, may be of Upper Cretaceous age, and may represent the oldest sedimentary layer within the region.

It is therefore felt that all of the data available within the area is consistent with the proposition that this region was formed by sea-floor spreading during the mid-Cretaceous period, and that the East Faeroes Trough forms the northern extension of the Rockall Trough and the Faeroe-Shetland Channel.

5.4 The Norwegian Basin.

The magnetic profiles obtained during the Durham cruises have enabled anomalies 23 and 24 to be positively identified within the Norwegian Basin. It is suggested that the transition from oceanic to continental crust occurs immediately landward of anomaly 24 (figure 3.7) implying that the opening of the Norwegian-Greenland Sea began approximately 60 M.y. ago, in line with the time proposed for the opening of the northern North Atlantic between Greenland and Rockall (Vogt and Avery, 1974).

It has been shown that anomalies 20 - 24 are parallel to each other within the eastern Norwegian Basin, indicating that they were formed on the same side of a single spreading axis. It is not possible to identify anomalies younger than anomaly 20. The new data confirms that the magnetic anomalies form a fan-shaped pattern within the Norwegian Basin, but as anomalies 20 - 24 are parallel to each other on each side but not on opposite sides of the basin, the fan-shaped pattern must have been created after anomaly 20 time. The half-spreading rate of the Mohns Ridge between anomaly 20 time and anomaly 7 time was 0.63 cm/year (Talwani and Eldholm, 1977), thus Greenland and Norway must have separated by 280 km during the 22 M.y. between these anomalies. It is not possible to accommodate such a width of ocean floor between anomaly 20 on either side of the axis in the south of the basin, although it is just possible to accomodate it in the extreme north of the basin. It is not feasible to account for this by a rotation of the Greenland and Eurasian plates, so a complementary zone of oceanic crust must exist to the west of the Norwegian Basin in order for there to be a constant width of oceanic crust from north to south. This was recognised by Talwani and Eldholm (1977) who proposed that the triangular region immediately to the south of the Jan Mayen Ridge (figure 5.1) formed the complementary zone.

The data gathered during the Durham cruises does not provide any new direct evidence relating to the evolution of the basin, but certain inferences can be drawn from some aspects of the data. As the evolution of the basin cannot have involved any rotation of the separating plates, the eastern boundary of the Norwegian Basin must be parallel to the western boundary of the complementary zone, so that the amount of oceanic crust generated remains constant from north to south.

This was noted by Talwani and Eldholm (1977) who showed that the western boundary of their proposed complementary zone is parallel to the northern section of the Faeroe-Shetland Escarpment, which they regard as the continent-ocean boundary in the eastern Norwegian Basin. However, the northern Faeroe-Shetland Escarpment has been shown to be a local feature which does not denote the continent-ocean boundary, and the boundary proposed in this thesis is not parallel to the western boundary of the complementary zone proposed by Talwani and Eldholm. The geometrical argument in favour of this area being the complementary zone is therefore invalid. Detailed investigation of the western margin of the Norwegian Basin and of the Jan Mayen Ridge area is required to delineate the position of the complementary zone.

The seismic reflection profile along line 9/77R detected numerous seamounts but failed to reveal any internal structure within these mountains. A correlation has been noted between the onset of these features and the disappearence of the identifiable linear magnetic anomalies. These seamounts lie entirely within the central part of the fan of anomalies and are separated by what appears on the seismic reflection records to be normal ocanic crust. Furthermore almost all of these features lie to the west of the extinct axis about which anamalies 20 - 24 were generated. It is possible that the seamounts were created by numerous small westward jumps of the spreading axis after anomaly 20 time as the axis sought to adjust to the presence of a complementary spreading axis to the southwest. Such behaviour would also explain the absence of correlatable linear magnetic anomalies within the centre of the fan.

References

AM, K. 1970. Aeromagnetic investigations on the Continental Shelf of Norway, Stadt-Lofoten (62^o-69^oN). Norg. geol. Unders. 266, 49-61.

AM, K. 1972. The arbitrarily magnetized dyke: interpretation by characteristics. Geoexploration 10, 63-90.

ANONYMOUS 1972. Formats for marine geophysical data exchange. Natn. Acad. Sci.-Natn. Res. Coun., 19pp.

AVERY, O.E., BURTON, G.D., and HEIRTZLER, J.R. 1968. An aeromagnetic survey of the Norwegian Sea. J. geophys. Res. 73, 4583-4600.

BATH, M. 1960. Crustal structure of Iceland. J. geophys. Res. 65, 1793-1807.

BOTT, M.H.P. 1973. The evolution of the Atlantic north of the Faeroe Islands. In:- Tarling, D.H. and Runcorn, S.K. (Editors). Implications of continental drift to the earth sciences 1, 175-189. Academic Press, London and New York.

BOTT, M.H.P. 1974. Deep Structure, evolution and origin of the Icelandic transverse ridge. In:- Kristjausson, L. (Editor). Geodynamics of Iceland and the North Atlantic area 33-47. D. Reidel Publishing Co., Dordrecht.

BOTT, M.H.P 1975a. Structure and Evolution of the North Scottish Shelf, the Faeroes Block and the intervening Region. In:- Woodland, A.W. (Editor). Petroleum and the Continental Shelf of North West Europe 1, Geology, 105-113. Applied Science Press.

BOTT, M.H.P. 1975b. Discussion. In:- Woodland, A.W. (Editor). Petroleum and the Continental Shelf of North West Europe 1, Geology, p.91. Applied Science Press.

BOTT, M.H.P. 1978. The origin and development of the continental margins between the British Isles and Southeast Greenland. In:- Bowes, D.R. and Leake, B.E. (Editors). Crustal Evolution in northwestern Britain and adjacent regions. Geological Journal Special Issue No.10, 377-392.

BOTT, M.H.P., BROWITT, C.W.A. and STACEY, A.P. 1971. The deep structure of the Iceland-Faeroe Ridge. Marine geophys. Res. 1, 328-351.

BOTT, M.H.P., NIELSEN, P.H. and SUNDERLAND, J. 1976. Converted P-waves originating at the continental margin between the Iceland-Faeroe Ridge and the Faeroe Block. Geophys. J.R. astr. Soc. 44, 229-238.

BOTT, M.H.P., SUNDERLAND, J., SMITH, P.J., CASTEN, U. and SAXOV, S. 1974. Evidence for continental crust beneath the Faeroe Islands. Nature, Lond, 248, 202-204

BOTT, M.H.P. and WATTS, A.B. 1970. Deep sedimentary basins proved in the Shetland-Hebridean continental shelf and margin. Nature, Lond. 225, 262-268.

BOTT, M.H.P. and WATTS, A.B. 1971. Deep Structure of the continental margin adjacent to the British Isles. In:- Delany, F.M. (Editor). The Geology of the East Atlantic Continental Margin, Symposium, Cambridge. I.G.S. Report 70/14, 89-109. H.M.S.O.

BOYD, L.A. 1948. The coast of northeast Greenland. Special Paper American Geographical Society, Number 30.

BULLARD, E., EVERETT, J.E. and SMITH, A.G. 1965. The fit of the continents around the Atlantic. Phil. Trans. R. Soc. Lond. A258, 41-51.

CASTEN, U. 1973. The Crust beneath the Faeroe Islands. Nature phys. Sci. 241, 83.

CHALMERS, J.A., DOBINSON, A., MOULD, A. and SMYTHE, D.K. 1977. Geophysical Evidence on the structure of the Faeroe-Shetland Escarpment. Geophys. J.R. astr. Soc. 49,288 (abstract).

DANGEARD, L. 1928. Observations de geologie sous-marine et d'oceanographie relatives a la manche. Annls. Inst. oceanogr. 6, 295.

DINGLE, R.V. 1976. A review of the sedimentary history of some post-Permian continental margins of Atlantic-type. Anais. acad. bras. Cienc. 48 (Supplement), 67-80.

DOBINSON, A. 1970. A magnetic survey of the Faeroe Bank. Ph.d. Thesis, University of Durham.

D.S.D.P. Scientific Staff, 1970. Deep Sea Drilling Project Leg 12. Geotimes 15, 10-14.

ELDHOLM, O. 1970. Seismic refraction measurements on the Norwegian Continental Shelf between 62° and 65° North. Norsk Geologisk Tidsskrift 50, 215-229.

ELDHOLM, O. 1978. Observations on the margin off Norway (65-70°N) and the history of early Cenozoic rifting. In:- Ramberg, I.B. and Neumann, E-R. (Editors). Tectonics and Geophysics of Continental rifts. Proceedings of the NATO A.S.I. Palaeorift Systems with Emphasis on the Permian Oslo rift, Volume 2, 229-236. D. Reidel Publishing Co., Dordrecht.

ELDHOLM, O. and WINDISCH, C.C. 1974. Sediment distribution in the Norwegian-Greenland Sea. Geol. Soc. Am. Bull. 85, 1661-1676.

ELLETT, D.J. and ROBERTS, D.G. 1973. The overflow of Norwegian Sea Deep Water across the Wyville-Thomson Ridge. Deep Sea Research 20, 819-835.

EWING, J. and EWING, M. 1959. Seismic refraction measurements in the Atlantic Ocean basins, in the Mediterranean Sea, on the Mid-Atlantic Ridge, and in the Norwegian Sea. Geol. Soc. Am. Bull. 70, 291-318.

FEATHERSTONE, P.S., BOTT, M.H.P. and PEACOCK J.H. 1977. Structure of the continental margin of south-eastern Greenland. Geophys. J.R. astr. Soc. 48, 15-27.

FLEISCHER, U. 1971. Gravity surveys over the Reykjanes Ridge and between Iceland and the Faeroe Islands. Marine Geophys. Res. 1, 314-327.

FLEISCHER, U., HOLZKAMM, F., VOLLBRECHT, K. and VOPPEL, D. 1974. Die struktur des Island-Faroer-Ruckens aus geophysikalischen Messungen. Sonderdruck Deutsch. Hydrographischen Zeitschr. 27, No. 3, 97-113.

FLINN, D. 1969. A geological interpretation of the aeromagnetic maps of the continental shelf around Orkney and Shetland. Geol. J. 6, 279-292.

FLINN, D. 1970. The Great Glen fault in the Shetland area. Nature, Lond. 227, 268-269.

FLINN, D., MILLER, J.A., EVANS, A.L. and PRINGLE, I.R. 1968. On the age of the sediments and contemporaneous Volcanic rocks of western Shetland. Scott. J. Geol. 4, 10-19.

GEOLOGICAL SURVEY, 1957. Geological map of Great Britain, Sheet 1, 2nd. Edition.

GIBB, F.G.F. and KANARIS-SOTIRIOU, R. 1976. Jurassic igneous rocks of the Forties Field. Nature, Lond. 260, 23-25.

GRØNLIE, G. and TALWANI, M. 1978. Geophysical Atlas, Norwegian-Greenland Sea. Vema Research Series Volume IV, Lamont-Doherty Geological Observatory, 26pp.

HALLAM, A. 1971. Mesozoic geology and the opening of the North Atlantic. J. Geol. 79, 129-157.

HEIER, K.S. and COMPSTON, W. 1969. Interpretation of Rb-Sr age patterns in high-grade metamorphic rocks, North Norway. Norsk Geologisk Tidsskrift 49, 257-283.

HEIRTZLER, J.R., DICKSON, G.O., HERRON, E., PITMAN, W.C. and LE PICHON, X. 1968. Marine magnetic anomalies, Geomagnetic Field Reversals, and the motions of the Ocean Floor and Continents. J. geophys. Res. 73, 2119-2136.

HEIRTZLER, J.R. and HAYES, O.E. 1967. Magnetic boundaries in the North Atlantic Ocean. Science 157, 185-187.

HEIRTZLER, J.R., LE PICHON, X. and BARON J.G. 1966. Magnetic anomalies over the Reykjanes Ridge. Deep Sea Research 13, 427-443.

HIMSWORTH, E.M. 1973. Marine Geophysical Studies between Northwest Scotland and the Faeroe Plateau. Ph.D. Thesis, University of Durham.

HINZ, K. 1972. The Seismic Crustal Structure of the Norwegian Continental Margin in the Vøring Plateau, in the Norwegian Deep Sea, and on the Eastern Flank of the Jan Mayen Ridge between 66° and 68°N. 24th Int. Geol. Congr., Section 8, 28-36.

HINZ, K. and MOE, A. 1971. Crustal Structure in the Norwegian Sea. Nature phys. Sci. 232, 187-190.

HOLTEDAHL, O. 1960. Geology of Norway. Norg. geol. Unders. 208.

HORNABROOK, J.T. 1967. Seismic interpretation problems in the North Sea with special reference to the discovery well 48/6-1. Proceedings of the 7th World Petroleum Congress 2, 837-862.

HUSEBYE, E.S., GJØYSTDAL, H., BUNGUM, H. and ELDHOLM, O. 1975. The seismicity of the Norwegian and Greenland Seas and adjacent continental shelf areas. Tectonophysics 26, 55-70.

INSTITUTE OF OCEANOGRAPHIC SCIENCES. 1974. Computer system for reduction, display and storage of navigation, gravity, magnetic and depth data recorded in the continental shelf or deep-ocean area. Manuals 1-12.

JEHU, T.J. and CRAIG, R.M. 1923. Geology of the Outer Hebrides. Parts 1-4. Trans. R. Soc. Edinb. 53, 419-441, 615-641; 54, 46-89; 55, 457-488; 57, 839-874.

JOHNSON, G.L. and HEEZEN, B.C. 1967. Morphology and evolution of the Norwegian-Greenland Sea. Deep Sea Research 14, 755-771.

JOHNSON, G.L., SOUTHALL, I.R., YOUNG, D.W. and VOGT, P.R. 1972. Origin and Structure of the Iceland Plateau and Kolbeinsey Ridge. J. geophys. Res. 77, 5688-5696.

KENNEDY, W.Q. 1946. The Great Glen Fault. Q.J. geol. Soc. Lond. 102, 41-72.

KHARIN, G.N. et. al. 1976. K/Ar age of the basalts of the Norwegian-Greenland Sea, D.S.D.P. Leg 38. In:- Talwani, M., Udinstev, G., et. al., Initial reports of the Deep Sea Drilling Project Volume 38, 755-761. U.S. Government Printing Office, Washington D.C., U.S.A.

KRISTOFFERSEN, Y. and TALWANI, M. 1977. Extinct triple junction south of Greenland and the Tertiary motion of Greenland relative to North America. Geol. Soc. Am. Bull. 88, 1037-1049.

LABRECQUE, J.L., KENT, D.V. and CANDE, S.C. 1977. Revised magnetic polarity time scale for Late Cretaceous and Cenozoic time. Geology 5, 330-335.

LARSON, R.L. and PITMAN, W.C. 1972. World-wide correlation of Mesozoic magnetic anomalies and its implication. Geol. Soc. Am. Bull. 83, 3645-3662.

LAUGHTON, A.S. 1972. The southern Labrador Sea - a key to the Mesozoic and early Tertiary evolution of the North Atlantic. In:- Laughton, A.S., Berggren, W.A., et. al., Initial reports of the Deep Sea Drilling Project Volume 12, 1155-1179. U.S. Government Printing Office, Washington D.C., U.S.A.

LAUGHTON, A.S. 1975. Tectonic evolution of the northeast Atlantic Ocean; a review. Norg. geol. Unders. 316, 169-193.

LAUGHTON, A.S., BERGGREN W.A., et. al. 1972. Initial reports of the Deep Sea Drilling Project Volume 12, 1243pp. U.S. Government Printing Office, Washington D.C., U.S.A.

LITVIN, V.M. 1964. Bottom relief in the Norwegian Sea. (in Russian). Trudy polyar. nauchno-issled. Inst. morsk. ryb. Khoz. Okeanogr. (P.I.N.R.O.) 16,89-109.

MATTHEWS, D.J. 1939. Tables of the velocity of sound in pure water and sea water for use in echo sounding and sound ranging. Admiralty Office, London. 52pp.

MEAD, G.D. 1970. International Geomagnetic reference field 1965.0 in Di-pole co-ordinates. J.geophys. Res. 75, 4372-4374.

MILLER, J.A. and MOHR, P.A. 1965. Potassium-Argon age determinations on rocks from St. Kilda. Scott. J. Geol. 1, 93-99.

MILLER, J.A., ROBERTS, D.G. and MATTHEWS, D.H. 1973. Rocks of Grenville age from Rockall Bank. Nature phys. Sci. 246, 61.

MOORBATH, S., SIGURDSSON, H., and GOODWIN, R. 1968. K-Ar ages of the oldest exposed rocks in Iceland. Earth Planet. Sci. Lett. 4, 197-205.

MOORBATH, S. and WELKE, H. 1969. Isotopic evidence for the Continental affinity of the Rockall Bank, North Atlantic. Earth Planet. Sci. Lett. 5, 211-216.

MORGAN, W.J. 1971. Convective plumes in the lower mantle. Nature, Lond. 230, 42-43.

NILSEN, T.H. and KERR, D.R. 1978. Paleoclimatic and Paleogeographic implications of a lower Tertiary laterite (latosol) on the Iceland-Faeroe Ridge, North Atlantic region. Geological Magazine 115, 153-182.

NISBET, H.C. 1961. The Geology of North Rona. Trans. geol. Soc. Glasg. 24, 169-184.

PALMASON, G. 1965. Seismic refraction measurements of the Basalt Lavas of the Faeroe Islands. Tectonophysics 2, 475-482.

PALMASON, G. 1967. Upper crustal structure in Iceland. Soc. Sci. Islandica 38, 67-78.

PITCHER, W.S. 1969. North-East trending Faults of Scotland and Ireland, a chronology of Displacement. In:- Kay, M. (Editor). North Atlantic - Geology and Continental Drift. Am. Ass. Pet. Geol. Mem. 12, 724-733.

PITMAN, W.C. and TALWANI, M. 1972. Sea-floor spreading in the North Atlantic. Geol. Soc. Am. Bull. 83, 619-646.

RABINOWITZ, P.D. and LABRECQUE, J.L. 1977. The Isostatic gravity anomaly: Key to the evolution of the ocean-continent boundary at passive continental margins. Earth Planet. Sci. Lett. 35, 145-150.

RASMUSSEN, J. and NOE-NYGAARD, A. 1970. Geology of the Faeroe Islands (Pre-Quaternary). Danmarks Geologiske Undersøgelse I. Raekke Nr. 25. Copenhagen 142pp.

ROBERTS, D.G. 1969. New Tertiary Volcanic Centre on the Rockall Bank, Eastern North Atlantic Ocean. Nature, Lond. 223, 819.

ROBERTS, D.G. 1975. Marine Geology of the Rockall Plateau and Trough. Phil. Trans. R. Soc. Lond. 278A, 447-509.

ROBERTS, D.G., ARDUS, D.A. and DEARNLEY, R. 1973. Precambrian Rocks drilled on the Rockall Bank. Nature phys. Sci. 244, 21-23.

ROBERTS, D.G., BISHOP, D.G., LAUGHTON, A.S., ZIOLKOWSKI, A.M., SCRUTTON, R.A. and MATTHEWS, D.H. 1970. New sedimentary basin on Rockall Plateau. Nature, Lond. 225, 170-172.

RONNEVIK, H., BERGSAGER, E.I., MOE, A., ØUREBØ, O., NAVREDSTAD, T. and STANGENES, J. 1975. The Geology of the Norwegian Continental Shelf. In:- Woodland, A.W. (Editor). Petroleum and the Continental Shelf of North West Europe 1, Goelogy, 117-128. Applied Science Press.

RUSSELL, M.J. 1976. A possible Lower Permian age for the onset of ocean floor spreading in the northern North Atlantic. Scott. J. Geol. 12, 315-323.

SABINE, P.A. 1965. Rockall: an Unusual Occurance of Tertiary Granite. Proc. geol. Soc. Lond. 1621, 51-65.

SAITO, T., BURCKLE, L.H. and HORN, D.R. 1967. Paleocene core from the Norwegian Basin. Nature, Lond. 216, 357-359.

SCHILLING, J.-G. and NOE-NYGAARD, A. 1974. Faeroe-Iceland Plume: Rare Earth Evidence. Earth Planet. Sci. Lett. 24, 1-14.

SCRUTTON, R.A 1972. The Crustal Structure of the Rockall Plateau Microcontinent. Geophys. J.R. astr. Soc. 27, 259-275.

SCRUTTON, R.A. and ROBERTS, D.G. 1971. Structure of Rockall Plateau and Trough, north-east Atlantic. In:- Delany, F.M. (Editor). The Geology of the East Atlantic Continental Margin, Symposium, Cambridge. I.G.S. Report 70/14, 81-88. H.M.S.O.

SELLEVOLL, M.A. 1975. Seismic refraction measurements and continuous seismic profiling on the continental margin off Norway between 62°N and 69°N. Norg. geol. Unders. 316, 219-236.

SMITH, P.J. and BOTT, M.H.P. 1975. Structure of the crust beneath the Caledonian foreland and Caledonian belt of the North Scottish shelf region. Geophys. J.R. astr. Soc. 40, 187-205.

SOPER, N.J., HIGGINS, A.C., DOWNIE, C., MATTHEWS, D.W. and BROWN, P.E. 1976. Late Cretaceous-early Tertiary stratigraphy of the Kangerdlugssauq area, east Greenland, and the opening of the north-east Atlantic. J. geol. Soc. Lond. 132, 85-102.

SRIVASTAVA, S.P. 1978. Evolution of the Labrador Sea and its bearing on the early evolution of the North Atlantic. Geophys. J.R. astr. Soc. 52, 313-357.

STEWART, F.H. 1965. Tertiary Igneous Activity. In:- Craig, G.Y. (Editor). The Geology of Scotland. Oliver and Boyd, Edinburgh 417-465.

SUNDVOR, E. and NYSAETHER, E. 1975. Geological outline of the Norwegian continental margin between 60° and 68°N. In:- Yorath, C.J., Parker, E.R. and Glass, D.J. (Editors). Canada's continental margin and offshore Petroleum Exploration. Can. Soc. Pet. Geol. Memoir 4, 267-281.

SYKES, L.R. 1965. The seismicity of the Arctic. Bull. seism. Soc. Am. 55, 501-518.

TALWANI, M. and ELDHOLM, O. 1972. The continental margin off Norway: A geophysical study. Geol. Soc. Am. Bull. 83, 3575-3608.

TALWANI, M. and ELDHOLM, O. 1974. The margins of the Norwegian-Greenland Seas. In:- Burk, C.A. and Drake, C.L. (Editors). The geology of continental margins. Springer-Verlag, New York 361-374.

TALWANI, M. and ELDHOLM, O. 1977. Evolution of the Norwegian-Greenland Sea. Geol. Soc. Am. Bull. 88, 969-999.

TALWANI, M. and UDINTSEV, G. 1976. Tectonic Synthesis. In:- Talwani, M., Udintsev, G., et. al., Initial reports of the Deep Sea Drilling Project Volume 38, 1213-1242. U.S. Government Printing Office, Washington D.C., U.S.A.

TARLING, D.H. and GALE, N. 1968. Isotopic Dating and Palaeomagnetic Polarity in the Faeroe Islands. Nature, Lond. 218, 1043-1044.

TORSKE, T. 1972. Tertiary oblique uplift of Western Fennoscandia; crustal warping in connection with rifting and breakup of the Laurasian continent. Norg. geol. Unders. 273, 43-48.

TRYGGVASON, E. 1962. Crustal Structure of the Iceland region from the dispersion of surface waves. Bull. seism. Soc. Am. 52, 359-388.

TRYGGVASON, E. 1964. Arrival times of P waves and upper mantle structure. Bull. seism. Soc. Am. 54, 727-736.

VINE, F.J. and MATTHEWS, D.H. 1963. Magnetic anomalies over ocean ridges. Nature, Lond. 199, 947-949.

VOGT, P.R. 1972. The Faeroe-Iceland-Greenland aseismic ridge and the western boundary undercurrent. Nature, Lond. 239, 79-81.

VOGT, P.R., ANDERSON, C.N., BRACEY, D.R. and SCHNEIDER, E.D. 1970 (a). North Atlantic magnetic smooth zones. J. geophys. Res. 75, 3955-3968.

VOGT, P.R. and AVERY, O.E. 1974. Detailed Magnetic Surveys in the Northeast Atlantic and Labrador Sea. J. geophys. Res. 79, 363-389.

VOGT, P.R., OSTENSO, N.A. and JOHNSON, G.L. 1970 (b). Magnetic and Bathymetric data Bearing on Sea Floor Spreading North of Iceland. J. geophys. Res. 75, 903-920.

WATTS, A.B. 1971. Geophysical investigations on the continental shelf and slope north of Scotland. Scott. J. Geol. 7, 189-218.

WHITEMAN, A.J., NAYLOR, D., PEGRUM, R. and REES, G. 1975. North Sea troughs and plate tectonics. Tectonophysics 26, 39-54.

WILSON, G.V., EDWARDS, W., KNOX, J., JONES, R.C.B. and STEVENS, J.V. 1935. The Geology of the Orkneys. Mem. Geol. Surv. Scott. 205pp.

WYROBEK, S.M. 1969. General appraisal of velocities of the Permian Basin of Northern Europe including the North Sea. Journal of the Institute of Petroleum 55, No. 541.

ZIEGLER, P.A. 1975. The geological evolution of the North Sea area in the tectonic framework of North-Western Europe. Norg. Geol. Unders. 316, 1-27.

ZVEREV, S.M., KOSMINSKAYA, I.P., KRASILSTCHIKOVA, G.A. and MIKHOTA, G.G. 1976. The Crustal structure of Iceland and the Iceland-Faeroe-Shetland region. In:- "Greinar V" Soc. Sci. Islandica 74-96.

ADDENDUM

HINZ, K. and WEBER, J. 1976. Zum geologischen Aufbau des Norwegischen Kontinentalrandes und der Barents-See nach reflexionseismischen Messungen. Erdöl und Kohle, Erdgas, Petrochemie, 3-29.

KRISTOFFERSEN, Y. 1977. Sea floor spreading and early opening of the North Atlantic. Earth Planet. Sci. Lett. 38, 273-290.

WILSON, J.T. 1963. Evidence from islands on spreading of ocean floors. Nature, Lond. 197, 536-538.

Appendix

The data from the 1976 cruise is stored on two magnetic tapes, labelled GPM501 and GPM502, which are held at the N.U.M.A.C. computing centre in Newcastle. These tapes contain the gravity, magnetic, bathymetric and navigation data, recorded in merged-merged format, and they are non-volume-labelled tapes. The data on the two tapes is basically the same, except that the gravity data on tape GPM502 is unfiltered whereas the gravity data on tape GPM501 has been filtered to remove spikes introduced during the redigitization of the gravity data.

Note:- The gravity base station values used to tie the 1976 survey were as follows:-

Barry Island	981 190·27	mgal
Lerwick Town	981 948·30	mgal

Details of the bases at Reykjavik and Manchester can be found in the thesis of A.G. Nunns.